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Analysis of Selected Knife Fertilizer Applicators for Grassland Improvement

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ANALYSIS OF SELECTED KNIFE FERTILIZER APPLICATORS FOR GRASSLAND IMPROVEMENT

BY

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APPLICATORS FOR GRASSLAND IMPROVEMENT

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser Date

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INTRODUCTION

A reduction of grassland acreage and a decline in production creates a demand for improving existing grassland. Nearly two-thirds of South Dakota's geographical area is in native grassland (50)*. An effective land use is made of much of this vast grassland acreage; however, it is not producing to its maximum capacity. Grassland acreage often receives minimum attention as most inputs of time, labor, capital, and management are put into the seemingly more valuable tilled cropland.

United States Department of Agriculture studies in the southern, north central, and northeastern states have indicated that proper pasture fertilization may increase pasture production from two to six times. This means possible increases in beef production for feeders and more milk production for dairies. Daily weight gain of steers on a fertilized alfalfa-brome mixture was 1.74 lb compared to 1.14 lb for steers on unfertilized pasture in a Minnesota experiment. A Pennsylvania State University study that compared milk production on fertilized and unfertilized birdsfoot trefoil and timothy pastures indicated that cows receiving fertilized forage produced approximately three times as much milk per year as that produced by the other cows feeding on unfertilized forage. The increasing of the protein content of the grass, the lengthening of the grazing season, the thickening of the

*Numbers in parenthesis refer to cited literature.

turf to decrease erosion, and the reducing of weed infestation are other fertilization benefits (14).

Soil nutrients need to be replenished from year to year. Nitrogen is a primary structural block in proteins, chlorophyll, and many other compounds of plant and animal matter (1). One method of nutrient replenishment is to apply commercial fertilizer. This is especially important for pastures and grassland since very little organic matter is annually returned and mixed into the soil by cultural practices.

Anhydrous ammonia, NH_3, is one of the common nitrogen carrier fertilizers. Nitrogen fertilizers include anhydrous ammonia, which is handled as a liquid under pressure, liquid solutions, and nitrogen compounds in a granular state. Anhydrous ammonia injected beneath the soil surface is adsorbed by clay particles and organic matter, and it becomes readily available for use upon nitrification (1). Anhydrous ammonia contains the most nitrogen, 82 percent by weight, of all commercial fertilizers. Also, modern production methods by the Haber process (29) have lowered the cost of anhydrous ammonia to be very economically competitive with other nitrogen fertilizers.

The price of anhydrous ammonia in the Brookings, South Dakota, vicinity in October, 1970, was 5 cents per lb of actual nitrogen compared with 9 cents per lb of nitrogen in ammonium nitrate, NH_4NO_3, which contains 34 percent nitrogen by weight. Respective prices in May, 1971, were 5 1/2 and 10 cents. Anhydrous ammonia is low in cost per unit of nitrogen. However, its grassland application has been limited because of the high application draft requirements, the need for special pressure equipment and applicators, and the question asked by many farmers--"How profitable is fertilizing grassland?" Less than 5 percent of the estimated 50 million acres of grassland in the north central and northeastern states are fertilized with nitrogen (46).

Granular fertilizer may remain inactive in the soil until moisture dissolves it and then leaches it to the grass root zone. Nitrogen left on the soil surface is subject to erosion loss (13). Anhydrous ammonia is placed in the root zone initially during its application. Although anhydrous ammonia has been used extensively on tilled land, information is relatively scarce on its use on grassland. A brief summary is given in the Review of Literature. Research is needed to learn more about the feasibility of using anhydrous ammonia as an effective, economical method of grassland improvement.

Other methods of grassland improvement in addition to fertilization include renovation by tilling and reseeding, but this method damages the established vegetation. Legumes and grasses interseeded in furrows, from which the sod has been removed, is a recently developed practice (43). This also impairs some of the plants. Consequently, a knife interseeder may be desirable to interseed sod while anhydrous ammonia or a liquid starter fertilizer is applied. Little vegetation would be ruined by the narrow blade.

A versatile applicator with flexible, individual units that could be used for fertilizing and interseeding grassland as well as fertilizing tilled soil would be beneficial to farmers and ranchers.

This would reduce the number of their required implements for crop production. Economical methods of pasture improvement could be used to great advantage to increase crop yield and to improve pasture quality and use.

OBJECTIVES

The objectives of this research on selected knife fertilizer applicators for grassland improvement are as follows:

1. Determine the influence of selected factors on draft requirements and functional performance of experimental knife applicators on grassland.
2. Investigate the economic feasibility of anhydrous ammonia application on grassland compared with top-dressing with ammonium nitrate considering fertilizer cost and cost of application.
3. Investigate the feasibility of interseeding legumes or other grasses with the experimental knife applicators while anhydrous ammonia or a liquid fertilizer is applied.

REVIEW OF LITERATURE

Brief History of Fertilization Developments

Since the beginning of recorded history, the farmer has been striving to improve plant growth and crop production. Although primitive man noticed that grasses grew better in areas littered with animal and plant residues, it was only 120 to 130 years ago when plants' requirements of certain elements in the soil were discovered (1).

During the 1840's John Bennet Lawes and J. H. Gilbert produced evidence in England showing that nitrogen, phosphorus, and potassium are very important in plant growth. Materials such as saltpeter and nitrate of soda containing these desired elements were sought and mined for fertilizer. Manure and other organic matter were also widely used (1).

Seventy years later Fritz Haber, a German chemistry professor, developed a laboratory procedure for synthesizing ammonia directly from hydrogen and atmospheric nitrogen. Haber's co-worker, Karl Bosh, improved the process to commercial scale production. This process, the Haber-Bosh process, is the foundation of today's ammonia industry from which 90 percent of the world's nitrogen compounds are produced (1, 29).

Concentrated commercial fertilizers were first used in the mid 1920's when southern California citrus groves were manually fertilized with calcium nitrate and ammonium sulfate. Hand labor was reduced in 1928 after Eugene and John Prizer built a system that dissolved soluble fertilizers and introduced them into irrigation water (29). A few years later Rosentein and Waynick initiated the use of anhydrous ammonia as a fertilizer in irrigation water (1, 29).

During the depression years of the 1930's it became apparent that large volumes of anhydrous ammonia sales for increased crop production were possible if anhydrous ammonia could be applied where irrigation was not practiced. A telephone company's underground cable laying equipment spawned the idea of releasing anhydrous ammonia beneath the ground surface. A tube was welded to the rear of a Killifer furrowing tool, and anhydrous ammonia was metered through a trailing hose added at the bottom of the tube. The hose contained the anhydrous ammonia until the furrow was sealed by a heavy drag following the knife. The method was considered successful because there was no evidence of escaping anhydrous ammonia from the onion-shaped retention pattern about the point of release (29).

During the past decade the general trend has been toward the use of liquid fertilizers and anhydrous ammonia in addition to granular materials (29). Efficient methods have been developed to handle these products. Savings in time and labor increase with the size of operation.

Fertilizer usage in the United States during the fiscal year ending June 30, 1970, totaled 39.4 million tons according to the Crop Reporting Board. This was a 1 percent increase from the previous year. Mixed fertilizer decreased by 2 percent from a year earlier, while primary nutrient materials used for direct application were up by 6 percent (47).

Farmers and manufacturers are vulnerable to regulatory measures on using agricultural chemicals because of ecological controversies (15, 25, 40). However, L. B. Nelson, Manager of Agricultural and Chemical Development for the National Fertilizer Development Center, Tennessee Valley Authority, has stated (15) that to the best of his knowledge "no sound scientific evidence has been obtained that indicated that fertilizers applied on farms are contributing significantly to the level of nutrients in water." George E. Smith (40), Director of Missouri Water Resources Center and Professor of Agronomy, University of Missouri, has emphasized that public concern of agricultural chemical contribution to pollution has been speculative, and only further research will expose the facts.

Today's farmer produces more products per capita than ever before. The imperative need of this production level must be properly communicated to the 95 percent nonfarming population. Thus the role of leadership is vital in the fertilizer industry (15, 25).

Grassland Fertilization

Soils are both chemically and biologically active, and applied fertilizers react with the soil and its living organisms. Reactions occur in cycles in which salts change from an available state to an unavailable state and then again to an available state for plant use. These reaction rates are influenced by temperature, moisture, and oxygen content which in turn affect the activity of the soil medium. The cycle ends when the nutrients are no longer available (30).

Virgin soils with little or no cultivation generally need fertilizers to correct existing soil deficiencies. Sixteen elements are known to be essential for plant growth. Nitrogen is often the first limiting nutrient in green pastures and requires continuous replacement in the North Central states. Phosphorus and potassium are less often deficient. Other elements are generally adequate in supply (1, 33).

Nitrogen's low cost has caused researchers to examine the profitability of fertilizing native pastures. Fertilizer applications increase profit from cool season grass and haylands in the Northern Plains and Northwest, but it may be difficult to justify on warm season grass as response is not consistent (42). Factors influencing the success of fertilization include soil type, soil fertility level, soil and air temperature, and amount and distribution of precipitation during the growing season (38). Depending on these factors, fertilization can be practiced where annual precipitation is as low as 10 inches. Fertilizer types and rates need to be matched to soil conditions and crops, but recommendations must be used only as guides where moisture is limiting (16, 17, 33, 37, 38). Also, proper grazing management cannot be neglected in providing optimum pasture use (35).

The basic objective of pasture fertilization is to maximize yield while maintaining grass-legume balance. Legumes may be encouraged by omitting nitrogen and applying phosphorus and potash. Pasture mixtures light in grass may be benefited by including nitrogen (33, 51). Nitrogen requirements may be adequately met by legumes making up 30 percent or more of a pasture mix, but if these pastures have been heavily grazed, spring applications of nitrogen may help stimulate early growth (35, 51).

McVickar et al. (29) reviewed three studies of fertilizer comparisons on grass. They reported Laughlin finding ammonium nitrate, ammonium sulfate, and calcium nitrate superior to anhydrous ammonia, urea, and calcium cyanamide as sources of nitrogen for the first bromegrass harvest after application. Burton and Johnson also obtained similar results on bermudagrass, but this was attributed to poor distribution of anhydrous ammonia. Anhydrous ammonia was found to be superior to calcium nitrate on boggy meadows, but Scholl et al. discovered that anhydrous ammonia did not stimulate growth as well as ammonium nitrate did on orchardgrass during a dry year.

In 1964 and 1965 Hill and Tucker (20) performed experiments in Oklahoma evaluating anhydrous ammonia, urea, and ammonium nitrate on bermudagrass. Yields were equal at low rates of application, while at higher rates anhydrous ammonia produced lower yields at the first cutting but higher yields than urea or ammonium nitrate in later cuttings. It was concluded that this lag was due to sod burn from poorly retained anhydrous ammonia.

A progress report of a three year Michigan State University experiment by Tesar et al. (45) indicated that pastures not fertilized with nitrogen yielded only 30 to 40 percent as much as nitrogen fertilized pastures. Ammonium nitrate and 20-in. spaced rows of anhydrous ammonia applications, 300 lb nitrogen per acre, were made on May 11, 1970, on an old alfalfa-grass pasture. The ammonium nitrate yielded 30 percent more production than the anhydrous ammonia produced by the tenth of July. But previous experience has shown that this difference has diminished by November 1. Hereford steers, 590 to 650 lb, gained equally well on the two fertilized plots and a control plot. No evidence of preferential grazing of anhydrous ammonia fertilized grass over nonfertilized grass between the rows was observed.

Additional Fertilization Characteristics

Anhydrous ammonia is a popular source of direct application nitrogen because its 82 percent nitrogen content reduces the amount of bulk handling. Anhydrous ammonia is a gas under normal atmospheric conditions and must be confined by pressure equipment. Visible vapors during application are often condensed water vapor, and gaseous anhydrous ammonia loss may actually be lower than indicated (11).

The cylindrical distribution pattern of applied anhydrous ammonia in the soil varies from 1 to 8 in. in diameter depending on soil conditions. Free anhydrous ammonia may persist in the soil for some time in some conditions, but normally upon application anhydrous ammonia reacts with the soil; then, positively charged ammonium and ammonium colloids are adsorbed by negatively charged clay and organic matter (1, 11, 29, 34). Adsorbed ammonium is nonleachable until it is converted to nitrate. Depth of application is not usually critical near optimum moisture conditions, but sealing may be best at greater depths, 4 in. or more (11).

The nitrification process begins at the periphery of the distribution pattern in the lower pH region and proceeds inward (28, 34). In warm, fertile soils where microbial activity is high, ammonium is converted within 4 to 8 weeks after application (11, 28). The nitrate forms are no longer bound and they move into the roots with the soil water (13). Autumn applications should be made when soil temperatures are 45 to 50 F and microbial activity has ceased. Then leaching losses will be at a minimum because nitrification has terminated for the season (11, 13, 29, 33, 34).

Parr and Engibous (34) have shown that anhydrous ammonia may persist in the retention zone as long as several weeks after application. Germinating corn seeds may be injured if planted closer than 4 or 5 in. to the retention zone. Deep applications, 6 in. or more, will provide a nutrient reserve, and possible injury to germinating seeds may be avoided. Later sidedressing applications should be made at least 5 in. to the side of the plant row.

In addition to application procedures, operators need to understand the hazards of anhydrous ammonia. Precautions need to be taken because serious accidents can cause blindness. Most accidents occur during transfer operations from nurse tank to applicator tank. Better equipment design and educational safety programs are needed to eliminate this unnecessary hazard (18).

Liquid fertilizers are often termed advantageous because of their solubility as well as ease of handling. Highly soluble fertilizers are beneficial as starters, making nutrients readily available for a germinating crop. The fertilizer is used by the crop before it is fixed by the soil. Final availability depends on its solubility after reacting with the soil. Application methods include broadcasting, knifing, and applying during planting or cultivating operations (26).

Liquid nitrogen solutions are of two types; nonpressure and low pressure. Nonpressure solutions contain nitrogen salts, and low pressure solutions contain ammonia alone or in combination with ammonium nitrate or urea. Trace elements and weed killers may be uniformly and effectively applied in nitrogen solutions (27, 38, 52). Liquid nitrogen solutions are as effective as granular forms or anhydrous ammonia if properly applied and managed. Low pressure solutions can be applied on or below the soil surface and still be effective (27).

Equipment and Costs

Sales literature reveals a wide variety of modern fertilizer application equipment. Excluding broadcasting equipment, applicators consist of three primary parts: storage tank, metering device, and applicator. Successful soil-penetrating applicators of many types are commercially available. Chisel tools fracture the soil and reduce knife side suction. Special shoe designs press anhydrous ammonia into the sides of the knife cut, and subsurface cutting wings expose more soil to the released anhydrous ammonia. Some knives are forward swept; others are back-swept or include coulters for use in trash. Spring tooth designs also exist (1, 26).

A high pressure injection method near the soil surface has been investigated for the purpose of avoiding the high power requirements of conventional applicators. Arya and Pickard (4) in 1956 concluded that nozzle design and their jets were more effective than extreme pressures in noncemented soils. With minimum pressures a maximum penetration may be obtained using intermittent injecting, rather than a smooth, continuous flow pattern. Hopkins et al. (21) designed and built seven different pressure injection applicators. The systems were workable, but their practicality depends on their effectiveness and on how much simplification can be made to minimize the cost.

Mink et al. (31) analyzed the effects of an air slide on anhydrous ammonia knives to reduce draft. Six applicators, 1/2 in. thick, with various air slots were moved 0.81 ft per second through an artificial soil at a 6-in. depth. Draft decreased as slot radius and air pressure increased. Although a 20.1 percent draft reduction was achieved when air pressure was 25 psig, pounds per square inch of gage pressure, using 1/4-in. slots, air horsepower exceeded draft horsepower by 3:1 at 5 psig to an extreme of 40:1 at 25 psig. Thus, air slides used in this manner may not be desirable for draft reduction since total energy required increased.

Mink et al. (31) noted that investigations have been made concerning the effects of oscillations and vibrations upon draft of a tillage tool. Reduction in draft by these methods may be as large as 75 percent. But greater fatigue stresses on the applicator, safety measures of anhydrous ammonia connections, and a more complex implement design requirement may render such a method of draft reduction impractical.

Cost of fertilizer application depends on fertilizer form and rate applied, area and acreage, and method of application such as custom, rental, or personal equipment. A North Dakota study showed that ownership of equipment to apply nonpressure nitrogen solutions is justified with over 1200 acres of annual use compared with rented equipment and over 360 acres compared with custom hiring. Respective breakeven points for a 3 1/2-ton trailer spreader include 1000 acres if rental equipment is available and 450 acres if custom hiring is available. Corresponding acreages for anhydrous ammonia are 270 and 175 (27).

Graphs of cost per acre vs. fertilized acreage for various fertilizer forms, application rates, and applicators are listed in Doane's Agricultural Report (11, 26, 27). Average 1970 custom rates per acre (no fertilizer costs included) for the North Central states were reported as follows (53): bulk, \$1.00; liquid, \$1.10; side dressing, \$1.50; aircraft, \$2.10; anhydrous ammonia, \$1.65; aqua ammonia, \$1.20. Fertilizer spreader rental was \$0.70 per acre. Hunt (23) listed typical Midwest custom rates of \$1.00 per acre for spreading fertilizer and \$2.00 per acre for applying anhydrous ammonia.

University agricultural economists in North Dakota, South Dakota, and Minnesota compiled 1971 custom rates of fertilizer application for their respective states (32). Charges included machine use, tractor costs, time and service of the operator, fuel, oil, and grease. Common charges varied from $0.50 per acre for granular application to $1.50 per acre for applying anhydrous ammonia. Specific rates are shown in Table 7.

A 1965 study in the Mississippi delta compared total cost of anhydrous ammonia with ammonium nitrate on 850 acres at a rate of 90 lb of nitrogen per acre. The costs averaged $6.73 per acre for anhydrous ammonia and $11.96 per acre for ammonium nitrate (29). In this Mississippi study storage and application costs of ammonium nitrate were $450 lower than that for anhydrous ammonia, but the cost of ammonium nitrate fertilizer was $4,400 higher than anhydrous ammonia. For 300 acres 90 percent of the total cost was ammonium nitrate compared with 64 percent of total cost for anhydrous ammonia. Percentages of total cost for fertilizer on 100 acres were 87 percent for ammonium nitrate and 70 percent for anhydrous ammonia. Costs per acre decline as fertilized acreage increases and efficiency of storage facilities and application equipment improves.

Tesar and Hansen (46) relate that anhydrous ammonia applications in 20-in. or even 30-in. rows could significantly increase yields in old grass pastures and fields. Based on 100 lb of nitrogen application per acre, the cost per extra ton of dry forage is about $5.00 when fertilized with anhydrous ammonia costing 4 1/2 cents per lb of nitrogen compared with $10.00 when fertilized with ammonium nitrate costing 10 cents per lb of nitrogen. Unfertilized grass yields of 1.5 to 2.0 tons of dry forage per acre should be doubled by fertilizing with anhydrous ammonia. This would double the carrying capacity per acre at one-half the cost of fertilizing with ammonium nitrate.

Interseeding

Since the mid 1950's interseeding has proven to be a successful, relatively low cost method of pasture improvement (8, 12). Interseeding consists of the shallow seeding of a legume or grass in furrows. Furrows are made by removing strips of sod 4 to 6 in. wide, 1 1/2 to 3 in. deep, and 2 to 3 ft apart (9, 43). Interseeding establishes more productive legumes and/or grasses in poor pastures. It is most commonly practiced in grassland areas which are too stony, too rough, or too erodible for complete renovation (10). As well as providing a firm seed bed, contoured furrows reduce runoff and decrease competition between young seedlings and existing vegetation (8, 35, 43). Each year since 1968 over 10,000 acres of South Dakota pasture land have been improved by interseeding (43).

Research is being conducted on varieties of alfalfa and grasses best for interseeding, methods and time of planting, fertilizers, and types of equipment. Alfalfa and alfalfa-grass combinations are most common since native pastures usually lack legumes. A common seeding rate is about 1 1/2 lb per acre, and cost of interseeding ranges from $6.00 to $8.50 per acre as determined from a study in seven central South Dakota counties (43).

"The value of using a starter fertilizer for interseeding has not been adequately demonstrated" (10, 51). Sod that has been fertilized by broadcasting normally competes with new seedlings. If band applicators are not available it is best to fertilize after seedlings are well established.

In 1960 an interseeder was constructed at the Southwestern Great Plains Research Center with emphasis on workability in heavy soils as well as in light textured soils. The furrow making devices were 18-in. sweeps with gage wheels to control the depth. Preliminary trials showed that a shield was needed to help remove dense sod from the furrow so that seedlings could emerge. Two separate seeding units were used, one for large seeds and another for small grasses or legumes. Fertilizer openers were mounted for fertilizer placement below and to the side of the seeded row. Double disk openers for seed placement, followed by a seed-firming wheel and drag chain, worked well in soft soils. A 1-in. wide stiff shank, followed by the press wheel and drag chain, gave better results in hard soil (12).

Decker _et al_. (8) successfully sod seeded birdsfoot trefoil in bluegrass in the northeastern United States. Concave disk openers appeared superior to conventional wing openers, but both were better than the grassland drill. Fertilizer was placed 1 to 1 1/2-in. deep, and seed was metered on the soil over the fertilizer.

In later research Decker _et al_. (9) interseeded crownvetch as well as birdsfoot trefoil in bluegrass pastures. The spreading growth characteristic of crownvetch makes it desirable for sod seeding. Paraquate was sprayed in a 15-cm band over the row in some plots to reduce competition from existing sod. Disk and disk-spear openers were better than a spear alone, but the spear gave satisfactory results when crownvetch was seeded with a paraquate application. Sod seeding with crownvetch gave production comparable to complete renovation or an annual application of 140 kg of nitrogen per hectare (125 lb nitrogen per acre).

At present, interseeding equipment is generally operated on a cooperative basis since individual farmer usage is infrequent. It is predicted that interseeding acreage will increase as more equipment with a better design becomes available and as farmers observe the improvements of renovated pastures (43).

DRAFT AND VERTICAL SOIL PENETRATING FORCE REQUIREMENTS OF ANHYDROUS AMMONIA APPLICATORS ON GRASSLAND

Applicator forces were measured to obtain draft requirements for the anhydrous ammonia applicators. Typical means of draft forces under various conditions were needed to compute estimated costs of anhydrous ammonia application on grassland.

Applicators and Instrumentation

The grassland knife applicators used in this research were experimental units designed by Clarence M. Hansen, Associate Professor of Agricultural Engineering at Michigan State University, under a grant-in-aid from USS Chemicals, Division of United States Steel Corporation.

The original applicator (Figure 1) included a spring-loaded parallel linkage for operation in rocky areas. The forward edge of the blade formed a 30° angle with the horizontal (a in Figure 1). The blade was hard surfaced on one side only so that it would wear to a sharp edge. A 1/8-in. anhydrous ammonia carrying pipe was welded to the rear of the knife, and it protruded through a 1 3/8-in. sweep, 11° above horizontal, formed from 1 1/4-in. nominal diameter pipe (Figure 2). A knife-slit closing sweep, formed from 1-in. pipe and welded to a 3/8- by 3-in. strap forming an angle of 5° below horizontal, was positioned behind the knife and over the knife sweep (Figure 2). Penetration depth was controlled by a 12-in. presswheel. It also assisted in closing the knife slit.

The author constructed coulter brackets and a 45° knife for the applicator (b in Figure 1). The 10-in. coulter had the ability to cut through trash to prevent it from collecting ahead of the blade. During the draft analysis the spring was replaced by a short length of tubing to fix the knife position with respect to the force transducer (Figure 3).

Michigan State University developed a second grassland anhydrous ammonia applicator, a forward-swept design (Figure 4). Better soil penetrating characteristics were obtained with this knife. The closing sweep was welded directly to the 1/4-in. thick blade about 2 1/2 in. above the bottom sweep. Shear bolts provided the only damage protection from rocks. Preliminary trials revealed that grass was collected by the knife's raking effect. A coulter was necessary to cut through trash.

Applicators were clamped to a 2 1/4-in. square, 3-point-hitch tool bar 8 ft in length. Tank capacity was 100 gallons, and anhydrous ammonia was metered by a Model A-3527 Blue Nitrolator through 3/8-in. inside diameter hoses to the applicators. A Ford 4000 SU diesel tractor supplied the power.

An instrument platform was bolted to the tractor frame so that the instruments could be controlled from the operator's seat (Figure 5). A two-channel oscillograph (Offner Type RS) recorded horizontal and vertical applicator force components. Force transducer details are described in Appendix A. Electrical power was provided by a

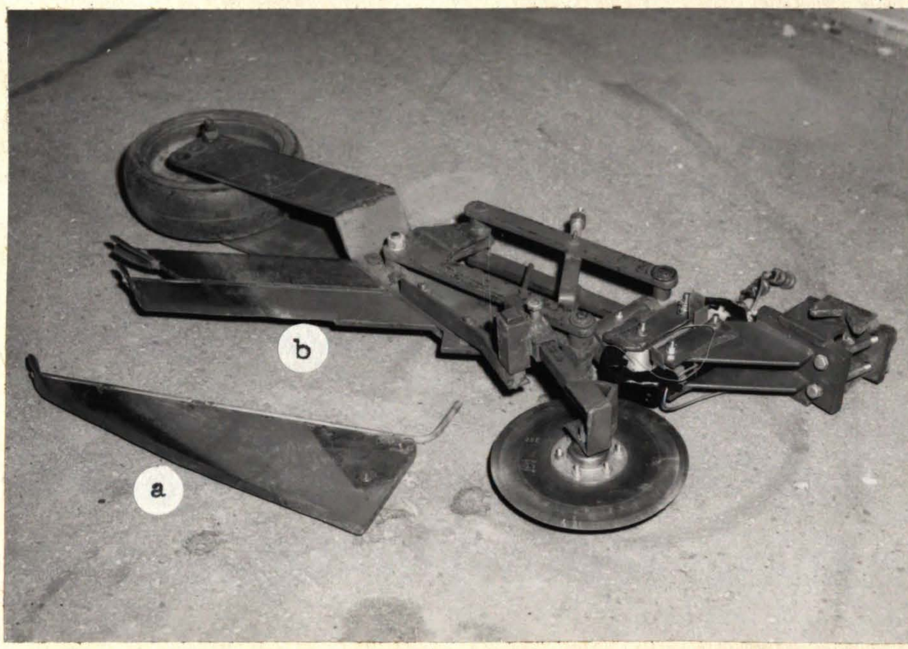

Figure 1. Experimental Applicator with Back-Swept Knives and a 10-in. Coulter
(a) 30° Knife
(b) 45° Knife

Figure 2. Knife-Slit Closing Sweep and Fertilizer Outlet

Figure 3. Strain Gage Force Transducer

Figure 4. Experimental Applicator with a Forward-Swept Knife and a Coulter

12-volt lead storage battery through a 275 watt, 100 volt a-c, 60 cycle power inverter (Ternado Continental Model 50-191).

Three applicators were mounted on the tool bar when draft tests were conducted (Figure 6). The testing applicator containing the force transducer was fixed to the center of the tool bar. A 30° back-swept knife applicator on either end of the tool bar stabilized the system. Since the tractor had wide-spaced front wheels there was no disturbance of the sod surface ahead of the applicator.

Experiment Design and Procedure

Anhydrous ammonia applicator force data were collected on an alfalfa-bromegrass pasture for three moisture conditions during the summer of 1971. The test location was north of Brookings, 1/2 mile north and 1/2 mile west of the junction of U.S. highways 14 and 77. Climatological data of this locality is available from the State Climatologist for South Dakota. Soil type was Lamoure silty clay loam, nearly level (48). Vegetation growth was 9 to 12 in. in height, and soil moisture was high during the first tests on June 3. Cattle grazed the pasture a few weeks later, and the grazed and trampled grass was clipped with a rotary mower before the second set of tests were conducted on August 4 while the soil conditions were very dry. The final draft tests in medium moisture conditions were made on August 23 shortly after the plot area had received 1 in. of precipitation.

Figure 5. Instrumentation for Recording the Applicator

Figure 6. Equipment for Force Measurements of the Forward-Swept Knife


CAUTION
Ammonia

Five knives, three speeds, two depths, and three replications formed the set of tests each time. The knives, speeds, and depths are described as follows:

K1 = 30° blade without coulter,

K2 = 30° blade with coulter,

K3 = 45° blade without coulter,

K4 = 45° blade with coulter, and

K5 = forward-swept knife with coulter.

Coulter penetration depth averaged about 1 in.

S1 = 3 mph,

S2 = 4 1/2, and

S3 = 6 mph.

D1 = 3 ± 1/2 in., press wheel in bottom hole or shallowest position (refer to Figures 1 and 4), and

D2 = 4 1/2 ± 3/4 in., press wheel in third hole from the bottom.

Each replication contained thirty 10- by 90-ft plots for the various combinations of factors (see Figure 7). Treatments were randomly assigned to the plots. To minimize the time required, the combination of a particular knife, speed, and depth was run in all three blocks before the next knife, speed, or depth was changed.

Soil measurements were taken to identify soil conditions for each set of force tests. Soil characteristics of moisture content, soil shear, soil-to-metal adhesion and friction, and penetration resistance were collected the day before the June 3 and August 4

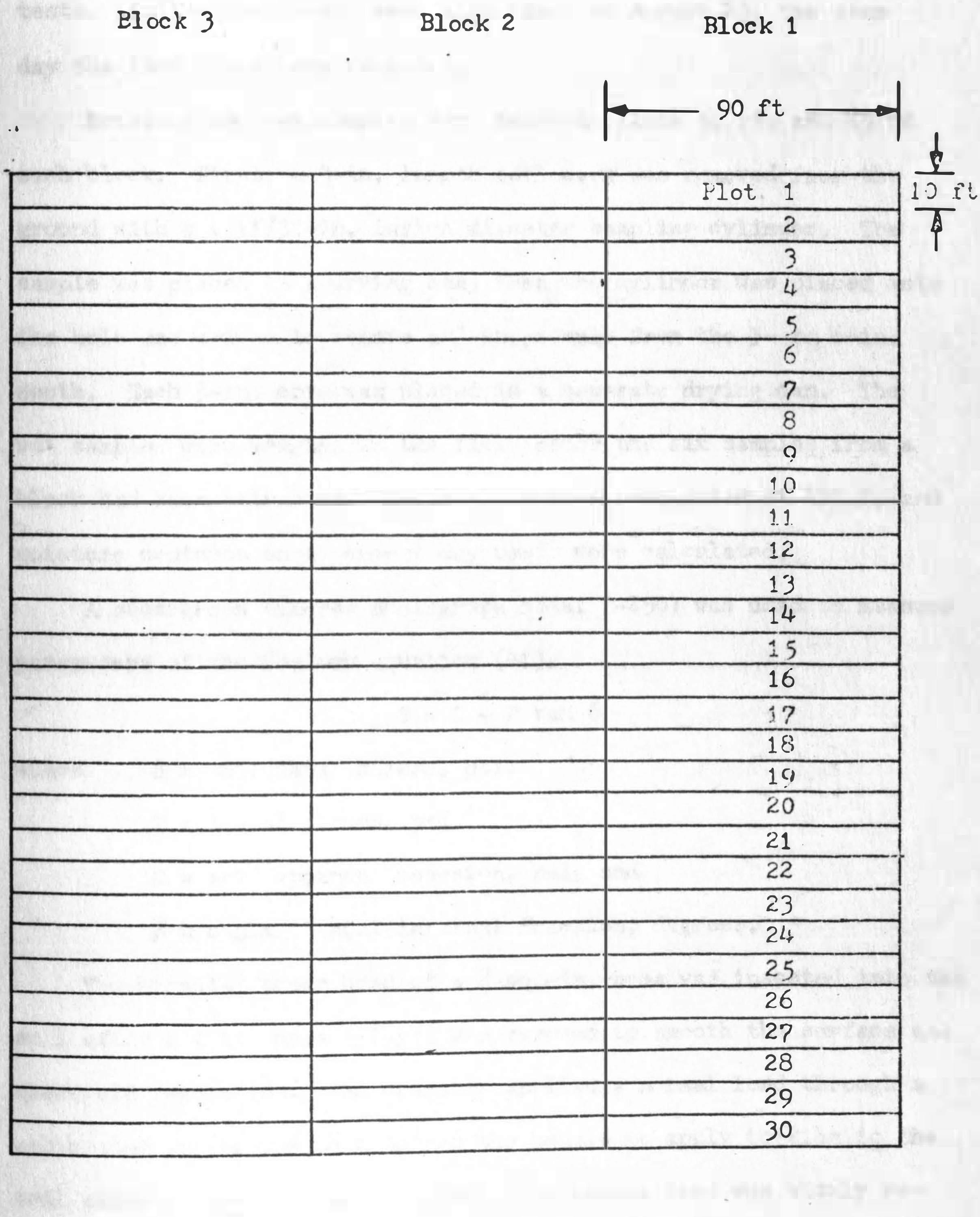

Figure 7. Replication and Plot Layout

tests. Soil measurements were also taken on August 23, the same day the last tests were recorded.

Moisture content samples were taken in plots 5, 15, and 25 of each block. First, a 3-in. length soil core was removed from the ground with a 1 11/32-in. inside diameter sampling cylinder. The sample was placed in a drying can; then the cylinder was placed into the hole and driven to remove a 3-in. sample from the 3- to 6-in. depth. Each 3-in. core was placed in a separate drying can. The wet samples were weighed in the field after the six samples from a block had been extracted. The samples were oven dried at 230 F, and moisture contents on a percent dry basis were calculated.

A sheargraph (Cohron Sheargraph Model D-250) was used to measure parameters of the Coulomb equation (41):

$$S = C + P \tan \phi$$

where S = soil shear stress, psi,

P = normal stress, psi,

C = soil apparent cohesion, psi, and

ϕ = angle of soil internal friction, degrees.

The circular shear head of a 2-sq.-in. area was inserted into the soil after a thin surface layer was removed to smooth the surface and clear old vegetation. The operator applied a normal load through a calibrated spring and then turned the handle to apply torsion to the soil sample. When the soil sheared, the normal load was slowly reduced. A marker recorded the shearing stress versus normal stress curve in units of psi on pressure sensitive paper. This was repeated

5 to 8 times for 3 to 5 different normal stresses per location. The Coulomb parameters were measured at 5 locations for the high and medium moisture conditions. No soil shear readings were taken for the driest condition since it was not possible to force the shear head into the dry, hardened soil without fracturing the sample.

Soil-to-metal adhesion and friction measurements were taken in a similar manner. A metal plug was inserted in the shear head, and the flat surface contacted the ground when the tests were made.

The upper and lower limits of the ultimate stress curve region were each approximated by one or two straight lines. The stress-curve region was bound by two lines on either side when the region was curved rather than linear. The Coulomb equations of these boundary lines were derived.

Soil resistance to a steady rate of penetration was measured by a cone penetrometer (41). A relationship between cohesion and penetration resistance exists in a purely cohesive soil. In a purely frictional soil the penetration resistance is related to the soil density and the angle of internal friction. The unit penetration resistance of the combined properties is expressed as a dimensionless value called the cone index although actual resistances are measured in pounds.

The standard cone consists of a 30° circular stainless steel cone of 1/2-sq.-in. base area fixed at the end of a 5/8-in. driving shaft containing depth markings. A proving ring force sensor with a dial indicator is located at the other end of the shaft. The cone was forced vertically into the soil at a rate of about 72 in. per minute, and the penetration resistances were noted at the instant the base of the cone was flush with the soil surface, and at the 2-in., 4-in., and 6-in. depth markings.

Cone index readings of plots 5, 10, 15, 20, and 25 in each block were recorded. Some locations in the plots of the driest condition were selective because the cone could not be forced to the 6-in. depth by the weight of the operator.

The soil characteristics are summarized in Table 1, and individual observations are listed in Appendix B.

Data Interpretation and Results

Horizontal forces or draft, F_x, and the vertical soil penetrating forces, F_z, were recorded by a two-channel oscillograph. The ink pens recorded the dynamic data on curvilinear graph paper fed at the rate of 25 mm per second. The force transducer was calibrated so the F_x scale was 40 lb per line or mm of pen deflection, and the F_z scale was 20 lb per line.

Two samples of 12.5 cm lengths (equivalent to 5 sec per sample) of F_x recorded chart data and the corresponding lengths of F_z data were marked on each run. The areas between the force data curves and the base zero force lines were measured with a compensating polar planimeter. Average forces were then computed by comparing the measured area to a nearly equal base area representing a known force. A data sample is shown in Figure 8.

Table 1. Summary of Soil Characteristics

Soil Measurement		High Moisture June 2, 1971	Medium Moisture August 23, 1971	Low Moisture August 3, 1971
Moisture Content % Dry Basis	Surface to 3-in. Depth	28.7	19.2	8.5
	3- to 6-in. Depth	20.1	15.9	11.0
Coulomb Equation	Soil Shear			
	$P = 0$ to 5 psi	$S = 0.6 + P \tan 42^{\circ}$	$S = P \tan 38^{\circ}$	----
	$P = 5$ to 18 psi	$S = 1.4 + P \tan 36^{\circ}$		
	Soil-to-Metal Resistance			
	$P = 0$ to 5 psi	$S = 0.8 + P \tan 31^{\circ}$	$S = P \tan 19^{\circ}$	$S = P \tan 20^{\circ}$
	$P = 5$ to 18 psi	$S = 2.0 + P \tan 20^{\circ}$		
Penetrometer Mean Cone Indexes at Listed Depths	Surface	51	50	82
	2 in.	77	101	165
	4 in.	94	123	179
	6 in.	121	163	201

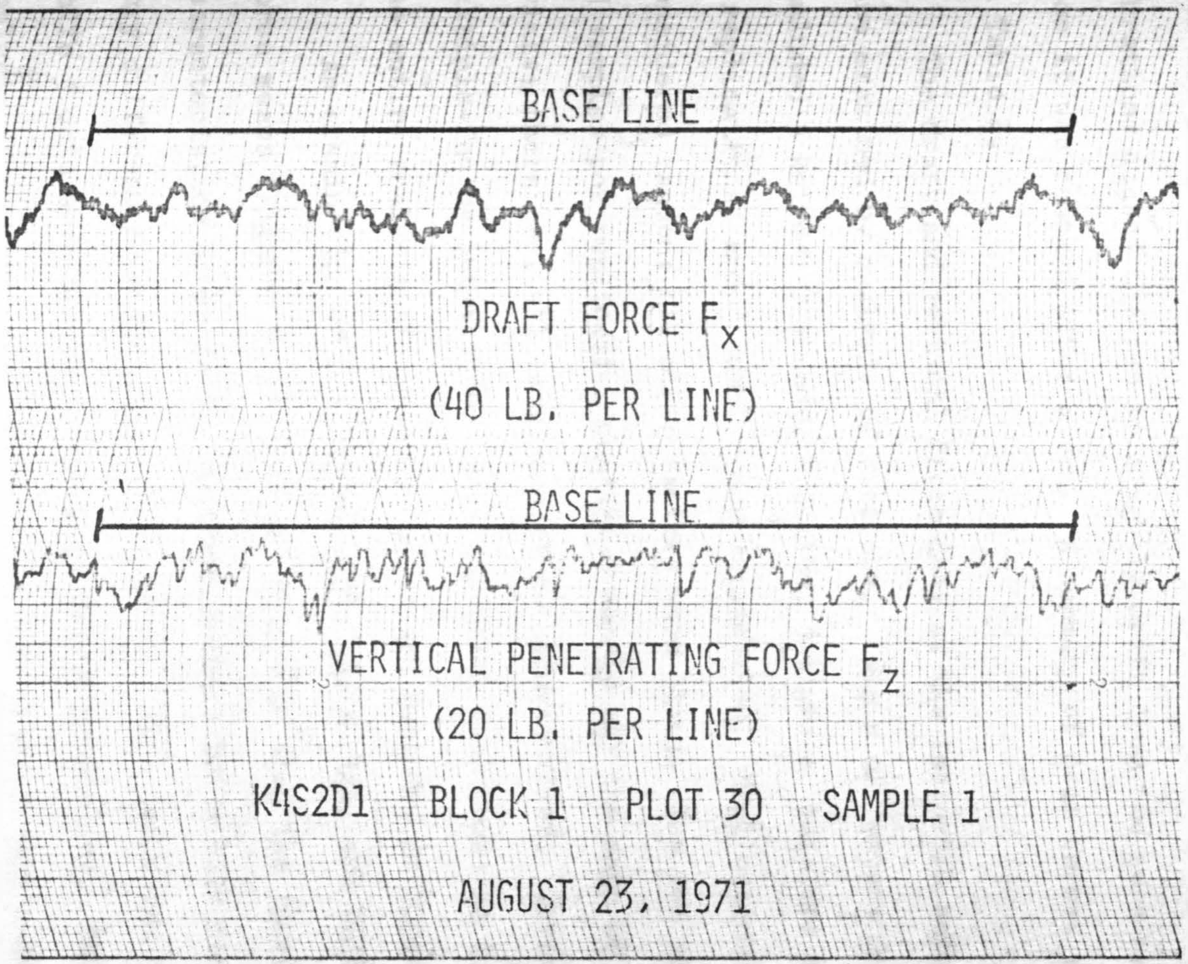

Figure 8. Sample of Force Data

Measured draft means were rounded to the nearest 10 lb since repeated planimetered measurements could be measured with that precision. The F_z data recordings were twice as sensitive as the F_x data but also rounded to the nearest 10 lb because the machinery vibrations caused the pen to slightly drift from the zero base line when it was checked after a run. A summary of mean forces is listed in Table 2.

The draft and vertical force data of the factorial experiment were examined by analysis of variance. Levels of factors initially included 5 knives, 3 speeds, 2 depths, 3 times or moisture conditions, 3 replications, and 2 samples per replication. Replications were considered random; all other factors were fixed. The two planimetered samples per replication contained nearly all the data of the 6 mph trials; therefore, all samples were considered fixed. Several multiple-factor interactions were significant as shown in Table 3. The entire analysis of variance tables are included in Appendix C.

An examination of the knife-depth, knife-time, and knife-speed force means (Figures 9, 10, and 11) indicated that the operating characteristics of knife 5, the forward-swept knife with coulter, were very different from the other four knives. This indicated that the knife 5 data were probably from a different population. Thus, the analysis of variance was repeated with the knife 5 data omitted. The summary is shown in Table 4.

The four-knife analysis was repeated with time 3 eliminated since the soil characteristics of time 3 were quite different compared

Table 2. Applicator Draft and Vertical Soil Penetrating Force Means

Knife Speed Depth Id.	Draft Force F_x (lb) High Moisture 6-3-71	Draft Force F_x (lb) Medium Moisture 8-23-71	Draft Force F_x (lb) Low Moisture 8-4-71		Soil Penetrating Force F_z (lb) High Moisture 6-3-71	Soil Penetrating Force F_z (lb) Medium Moisture 8-23-71	Soil Penetrating Force F_z (lb) Low Moisture 8-4-71	
K1S1D1	270*	320	460		120	110	160	
1 2 1	250	370	480		110	120	160	
1 3 1	260	360	470		120	120	160	
1 1 2	480	620	700		140	130	120	
1 2 2	470	660	790		150	130	130	
1 3 2	480	660	810	500**	150	140	140	130**
2 1 1	260	380	460		160	180	170	
2 2 1	240	320	440		150	150	160	
2 3 1	270	350	460		160	160	200	
2 1 2	500	560	780		230	190	240	
2 2 2	460	630	760		210	220	230	
2 3 2	460	610	760	480**	210	200	230	190**
3 1 1	260	380	500		160	200	180	
3 2 1	270	430	500		130	200	190	
3 3 1	250	380	530		160	160	180	
3 1 2	500	620	810		200	220	200	
3 2 2	480	600	820		200	190	200	
3 3 2	490	610	890	520**	160	210	140	180**
4 1 1	250	360	540		170	190	180	
4 2 1	260	400	490		150	180	180	
4 3 1	270	390	480		170	200	180	
4 1 2	480	550	830		240	250	200	
4 2 2	480	560	860		250	240	170	
4 3 2	470	560	830	500**	220	230	190	200**
5 1 1	390	250	490		50	30	60	
5 2 1	520	400	500		80	40	60	
5 3 1	560	410	540		80	40	60	
5 1 2	480	480	480		80	60	40	
5 2 2	540	470	490		80	30	50	
5 3 2	590	510	460	480**	120	30	50	60**

*Each mean is an average of 6 samples.

**Each mean is the knife average for 3 speeds, 2 depths, 3 moisture conditions, 3 replications, and 2 samples per replication.

Table 3. Analysis of Variance Summary of Five Knives

Significant Factors Influencing Draft

Significant at the 1% Level	Significant at the 5% Level
time	speed
depth	speed X knife
knife	depth X speed X knife
time X knife	
depth X knife	
time X depth X knife	
time X speed X knife	

Significant Factors Influencing Vertical Force

Significant at the 1% Level	Significant at the 5% Level
knife	depth
time X knife	time X depth
depth X knife	sample X time X knife
speed X knife	time X depth X knife
time X depth X speed X knife	

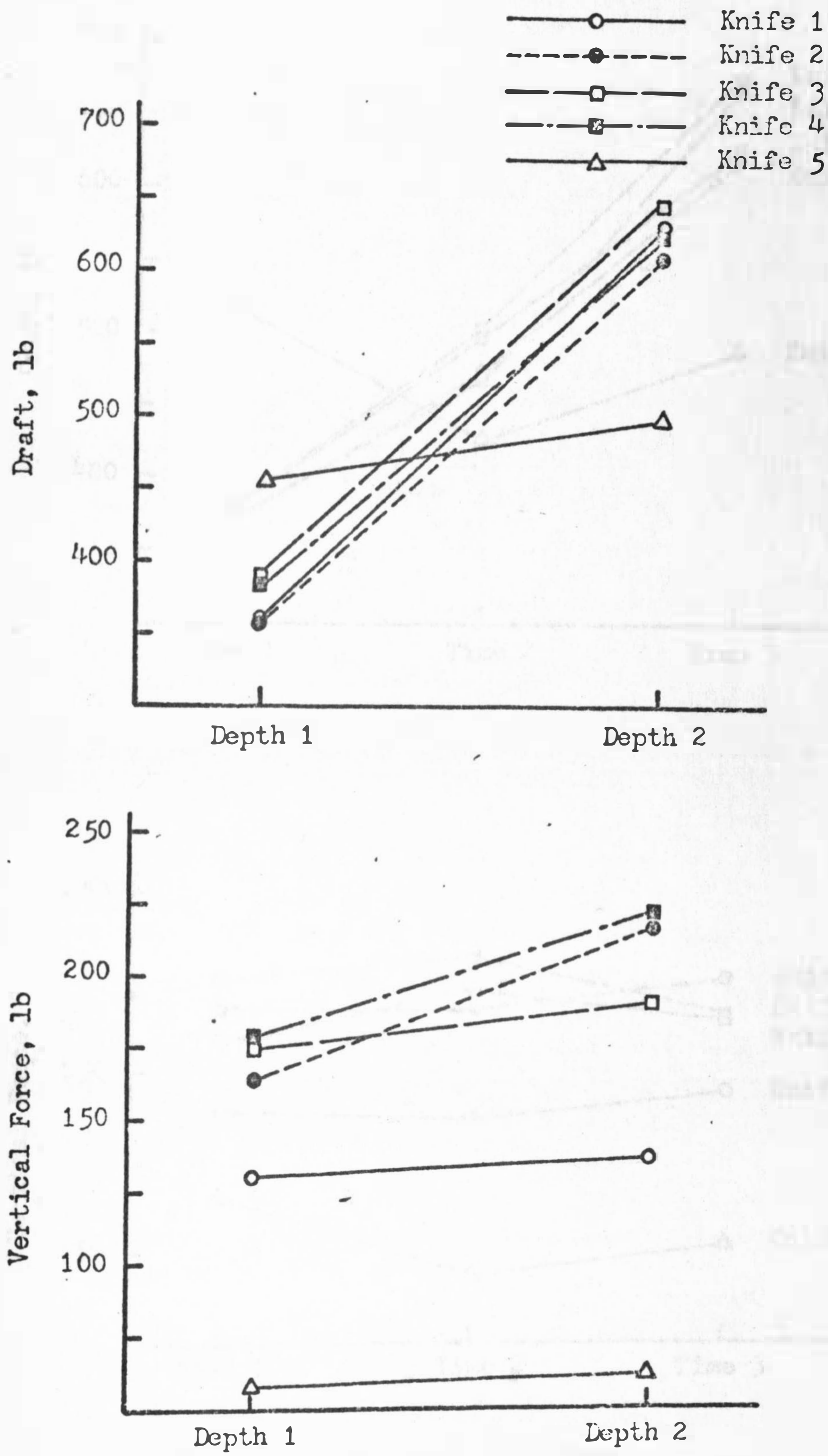

Figure 9. Knife-Depth Force Means

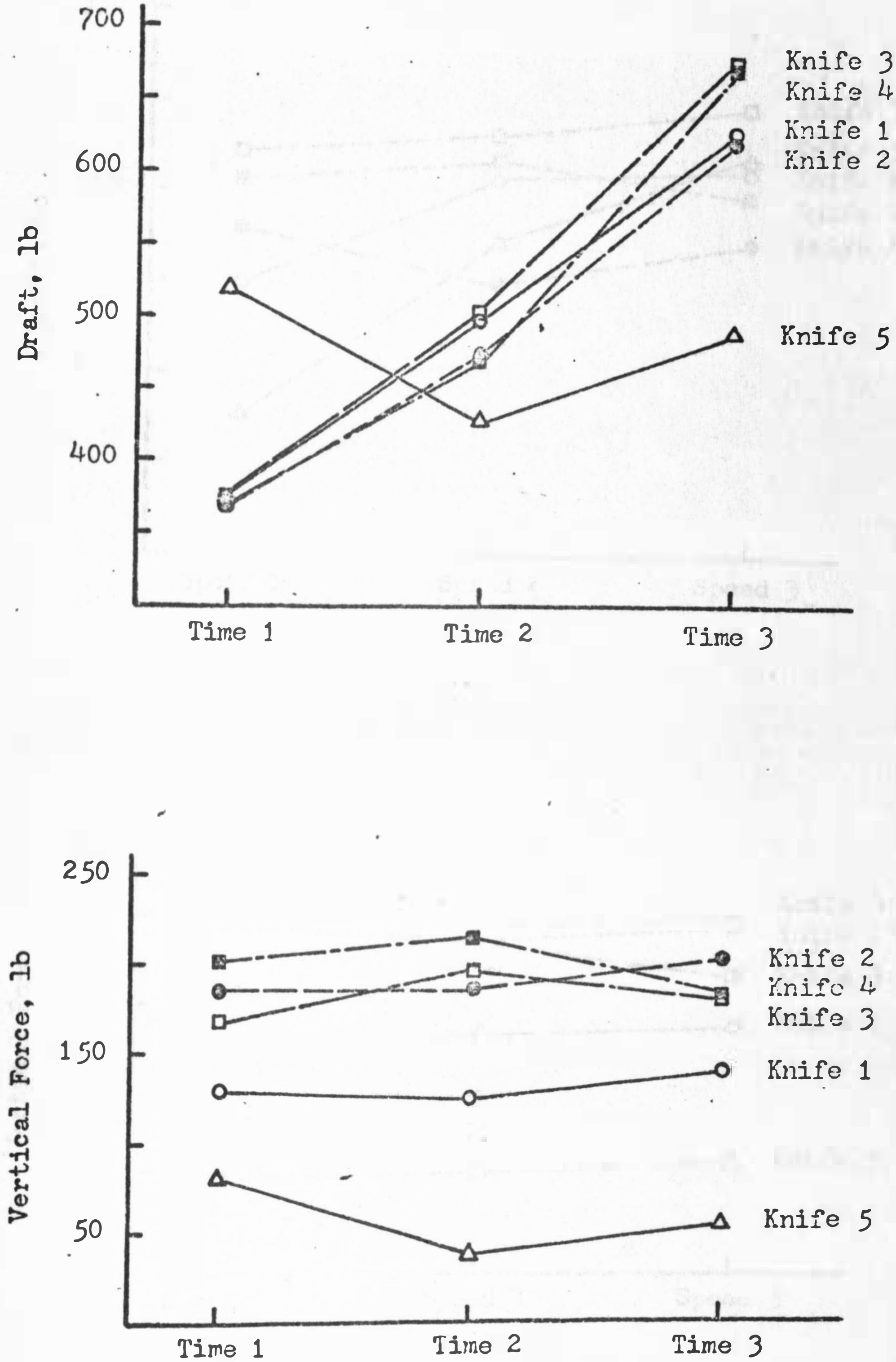

Figure 10. Knife-Time Force Means

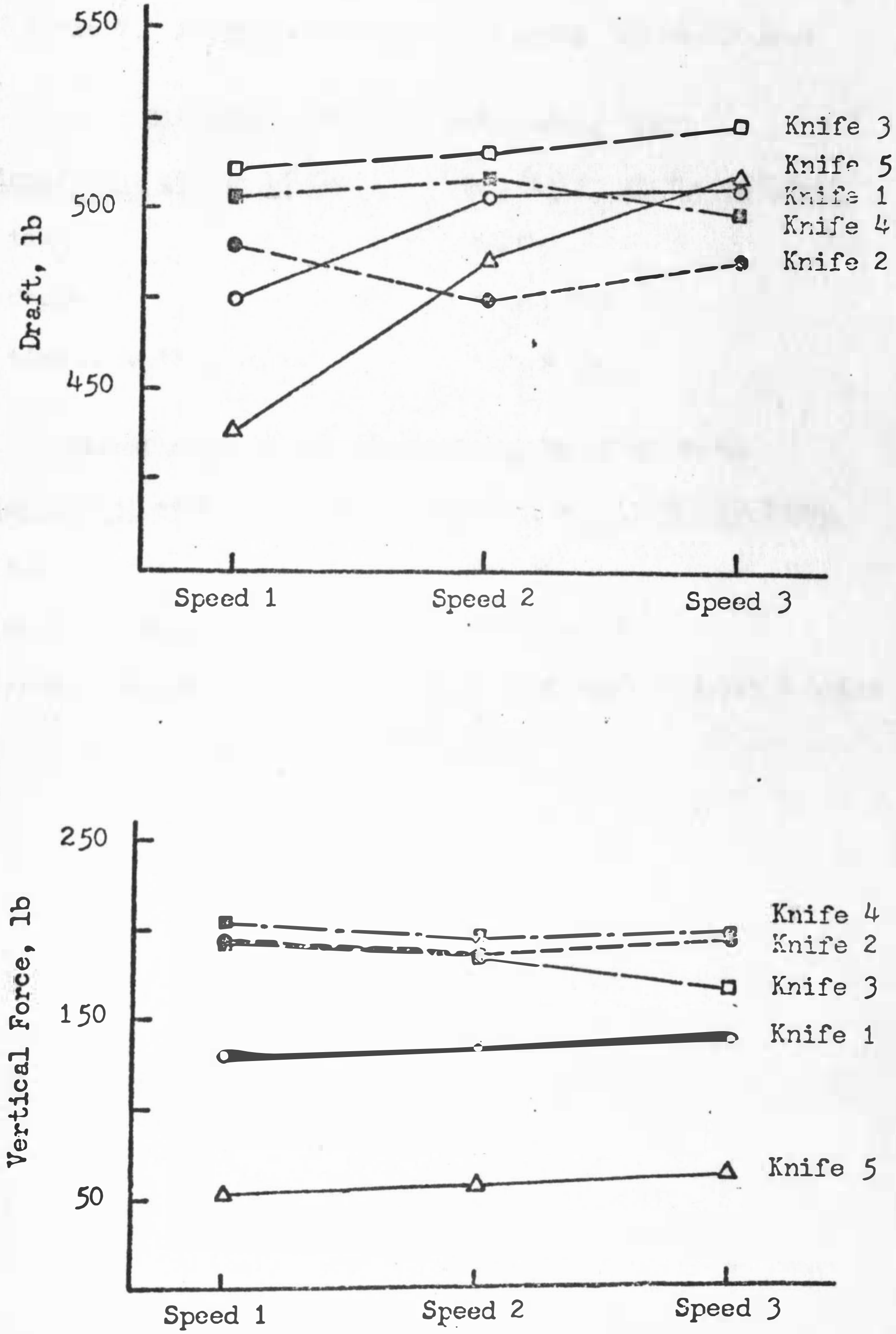

Figure 11. Knife-Speed Force Means

Table 4. Analysis of Variance Summary of Four Knives

Significant Factors Influencing Draft

Significant at the 1% Level	Significant at the 5% Level
time	knife
depth	time X knife
time X depth X knife	time X depth

Significant Factors Influencing Vertical Force

Significant at the 1% Level	Significant at the 5% Level
knife	depth
depth X knife	time X depth
speed X knife	time X depth X speed X knife

with the first two times. The profile of the dry soil moisture distribution was reversed compared with times 1 and 2 (refer to Figure 12). Penetration resistances were also much greater during time 3. Actual cone index means of time 3 in Figure 13 are low since some locations were selective when the cemented condition limited the cone penetration to less than a 6-in. depth. The analysis of variance summary of the four-knife data during the first two times is shown in Table 5.

The three-factor interaction, time X depth X knife, and the four-factor interaction, time X depth X speed X knife, were not caused by time 3 since they are still significant.

The plot of knife-depth force means of Figure 9 indicated that the interaction might be caused by a coulter effect. But the knife-time force means of Figure 10 indicated that differences might be caused by a knife-angle effect. Definite reasons for these interactions cannot be explained by the results of this analysis.

No significant force differences among speeds were apparent from the four-knife analysis of variance as contrasted to the five-knife analysis. No consistent force differences with speed can be interpreted from the knife-speed force means of Figure 11. The speed-time and speed-depth draft means (Figures 14 and 15) of the forward-swept knife, however, definitely increase with speed. The draft of the forward-swept knife increased approximately 16 percent as speed increased from 3 to 6 mph.

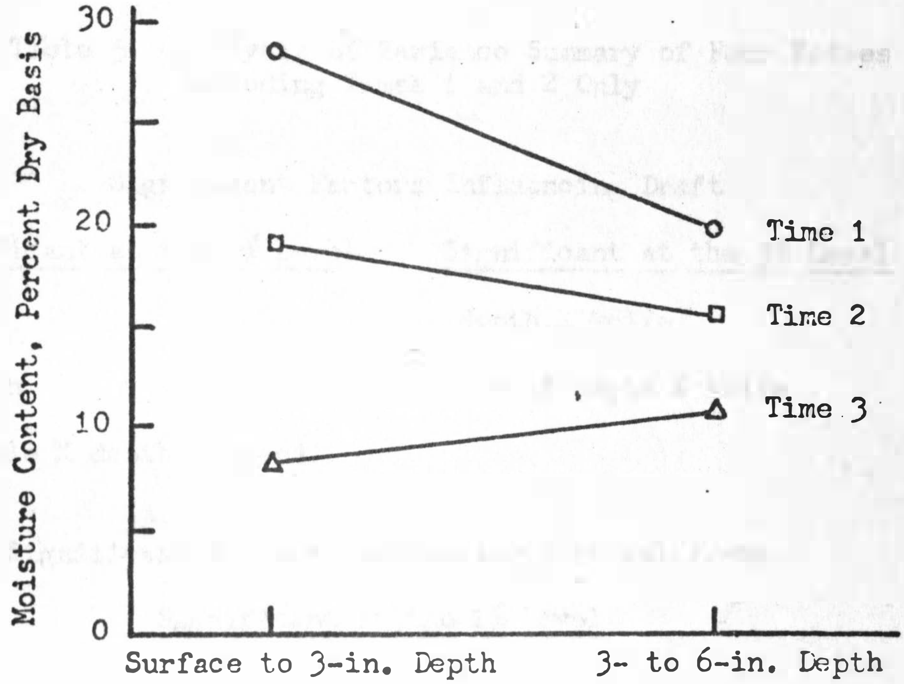

Figure 12. Moisture Content Means at Two Depths

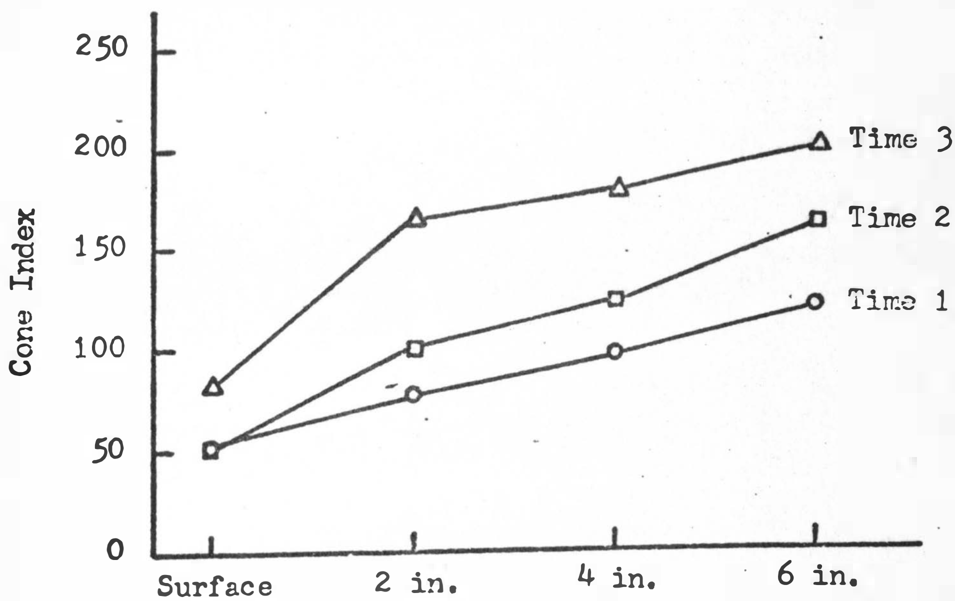

Figure 13. Cone Index Means at Four Depths

Table 5. Analysis of Variance Summary of Four Knives Including Times 1 and 2 Only

Significant Factors Influencing Draft

Significant at the 1% Level	Significant at the 5% Level
time	depth X knife
depth	time X depth X knife
sample X depth X speed	

Significant Factors Influencing Vertical Force

Significant at the 1% Level
depth
knife
depth X knife
time X depth X speed X knife

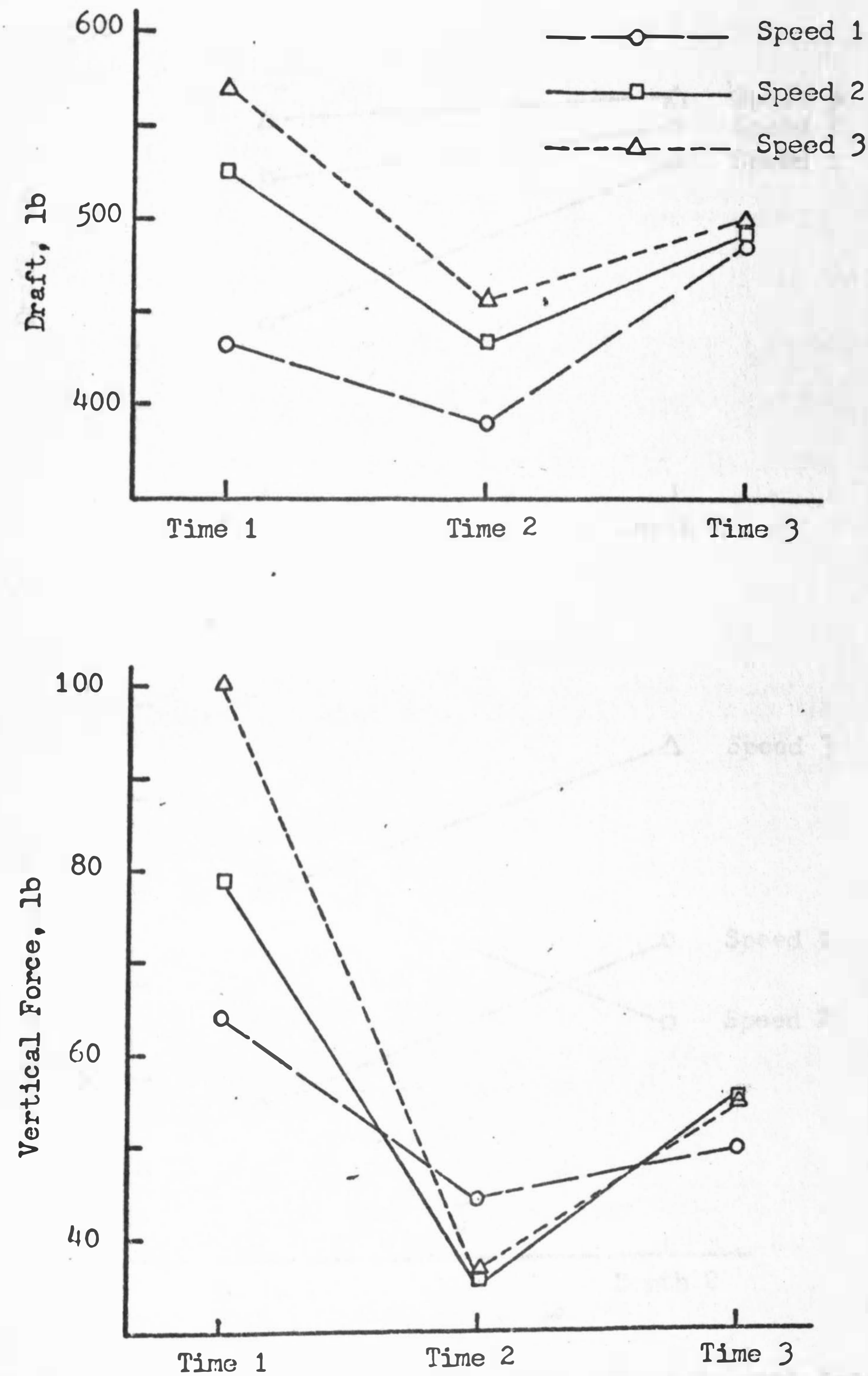

Figure 14. Speed-Time Force Means of the Forward-Swept Knife

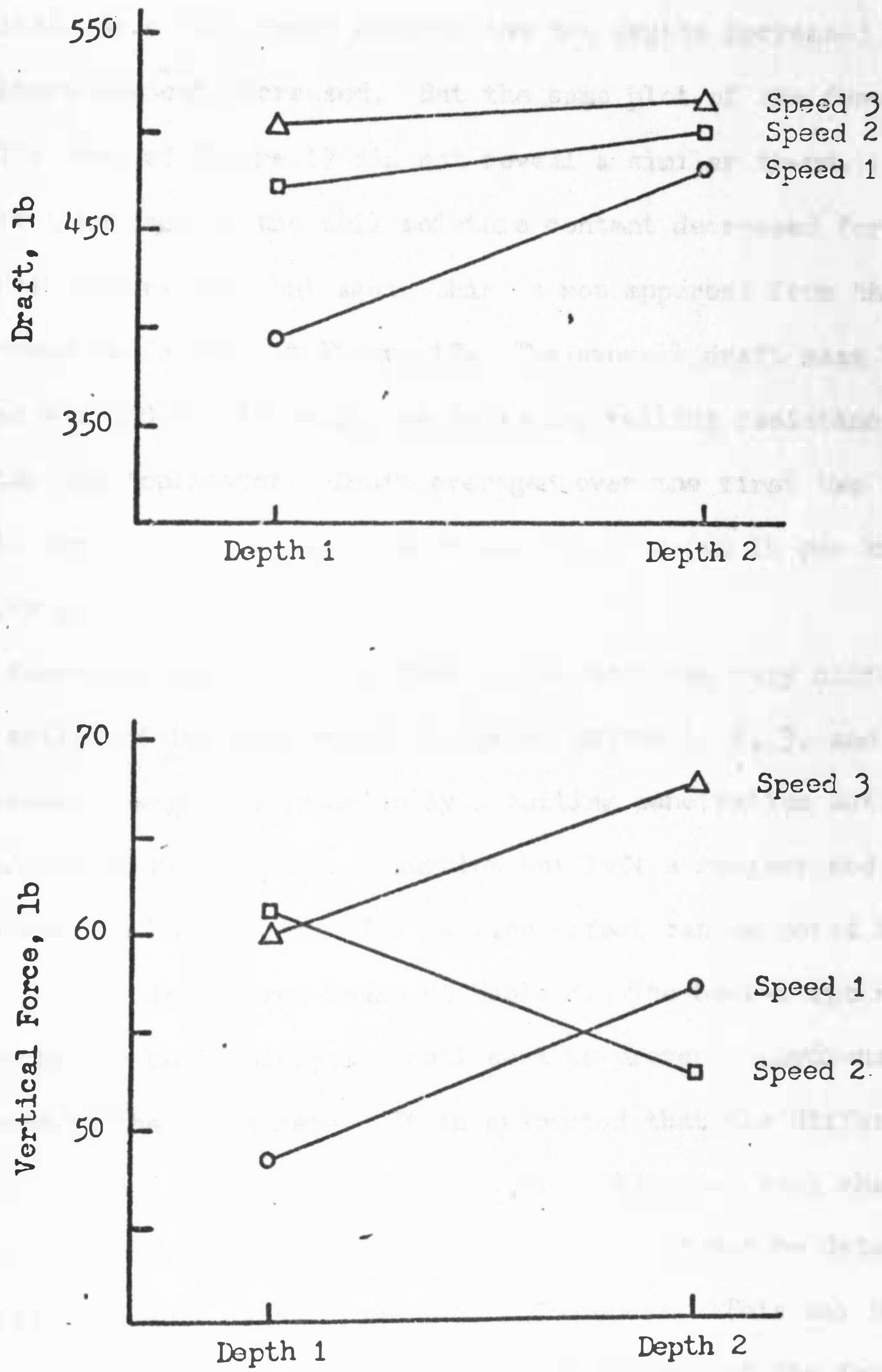

Figure 15. Speed-Depth Force Means of the Forward-Swept Knife

The four-knife time-depth force means of Figure 16 indicated that the vertical force difference between the two depths decreased as the soil moisture content decreased. But the same plot of the forward-swept knife data of Figure 17 did not reveal a similar trend.

Draft increased as the soil moisture content decreased for the four knives (Figure 16), but again this is not apparent from the forward-swept knife data in Figure 17. The overall draft mean of all conditions was 500 lb per knife not including rolling resistance of the tractor and applicator. Draft averaged over the first two times was 430 lb per knife. The draft mean increased to 600 lb per knife for the dry grassland condition.

The forward-swept knife's action on the soil was very different from the action of the back-swept design of knives 1, 2, 3, and 4. The back-swept design had essentially a cutting penetration action. The forward-swept knife had more suction but left a rougher sod surface along the knife slit. The suction effect can be noted by examining the vertical force means of Table 2. The back-swept applicators formed the best knife-slit soil seal to prevent anhydrous ammonia loss to the atmosphere. It is suspected that the different knife-soil actions, field irregularities with different soil characteristics, and possible depth variations which could not be detected by random measurements caused some data differences. This may have prevented additional observations about the influence of the factors on the applicator forces.

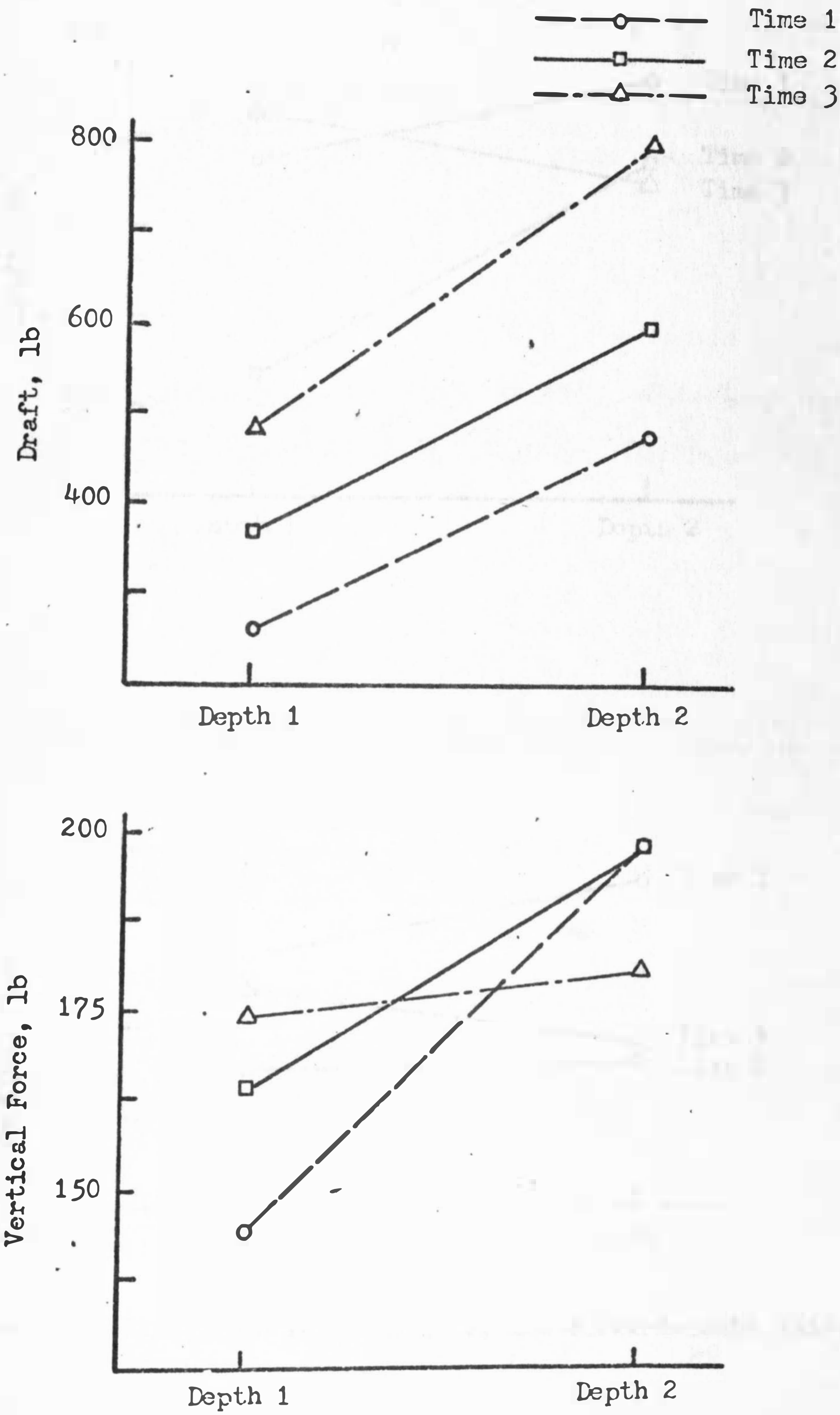

Figure 16. Time-Depth Force Means of Four Knives

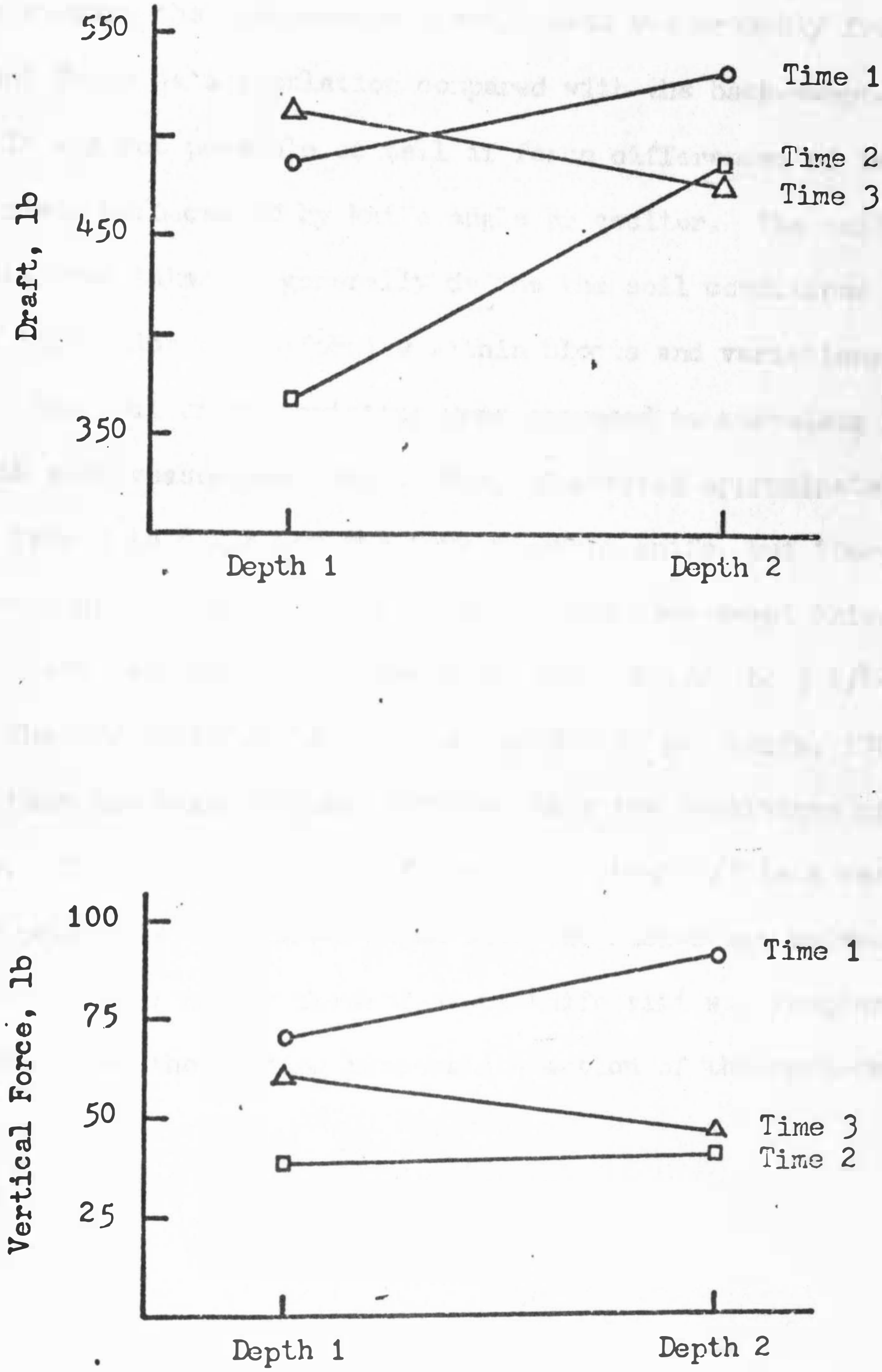

Figure 17. Time-Depth Force Means of the Forward-Swept Knife

In summary the forward-swept-knife data was probably from a different force data population compared with the back-swept-knife data. It was not possible to tell if force differences of the back-swept knives were caused by knife angle or coulter. The soil measurements were taken to generally define the soil conditions and to give an indication of uniformity within blocks and variations among blocks. The soil characteristics were not used to correlate force data with soil measurement data. Draft increased approximately 16 percent from 3 to 6 mph for the forward-swept knife, but there was no significant draft increase with speed for the back-swept knives. The overall draft mean was 500 lb per knife for a 2 1/2- to 5 1/4-in. depth. The dry grassland draft mean was 600 lb per knife, 170 lb greater than the mean obtained for the other two conditions of soil moisture. The forward-swept knife required about 2/3 less vertical force to penetrate the sod compared with the back-swept knives. But the sod surface along the forward-swept knife slit was rougher than that produced by the cutting penetration action of the back-swept knives.

COST COMPARISON OF ANHYDROUS AMMONIA AND AMMONIUM NITRATE APPLICATION

An economic comparison of anhydrous ammonia application with ammonium nitrate application to grassland requires a cost analysis. There is a substantial price difference per lb of available nitrogen favoring anhydrous ammonia over ammonium nitrate (Table 6), but the additional factor of large energy requirements of anhydrous ammonia applicators must be considered. Also, machinery costs must be estimated. These costs may be estimated from local custom rates; however, custom operator rates may be low for small operations but high compared with ownership costs if large acreages need to be fertilized.

Cost analysis methods were reviewed. Prices vary with time and location, fertilizer spreaders, and anhydrous ammonia applicators. In addition tractors of many sizes and characteristics exist. Thus, specific assumptions were made for the economic comparisons.

Custom Application

Typical custom rates for spreading ammonium nitrate and applying anhydrous ammonia are listed in Table 7. These rates probably apply to tilled cropland since grassland fertilization is minimal, but the rates were assumed to apply also to grassland. These rates include the cost of hiring the machine with tractor, fuel, oil, and operator, but fertilizer cost is excluded. Custom fertilizer application costs for selected price ranges of fertilizer costs and custom rates are shown in Tables 8 and 9 (23, 32, 53). The corresponding price ranges and percent savings by applying anhydrous ammonia rather than

Table 6. Examples of South Dakota Prices of Anhydrous Ammonia and Ammonium Nitrate Fertilizers During Summer, 1971*

Location	Price of NH_3 Per lb N (cents)	Price of NH_4NO_3 Per lb N (cents)
Aberdeen	5.4	8.3
Brookings	5.5	10.0
Canton	4.2	9.1
Egan	5.1	9.4
Volga	5.5	9.5
Winner	5.2	9.0

*Prices were obtained by private communication.

Table 7. 1971 Fertilizer Application Custom Rates, Cost per Acre

Fertilizer Application	South Dakota Most Common Rate	South Dakota Average Rate	Minnesota Most Common Rate**	North Dakota Most Common Rate	North Dakota Average Rate
Granular	\$0.50	\$0.69	\$0.50, \$0.75	\$0.50	\$0.65
Liquid	1.00	1.04	1.50	0.50	0.70
NH_3	1.50	1.36	1.50	1.00	1.35

**The first figure is from southwestern Minnesota; the second is from southeastern Minnesota.

Table 8. Cost per Acre Range of Custom Ammonium Nitrate Application

Custom Rate: \$0.50 to \$1.00 per acre

Ammonium Nitrate Cost: \$0.0850 to \$0.1000 per lb nitrogen

Application Rate per Acre	Fertilizer Cost	Custom Rate	Total Cost
30 lb	\$2.55- \$3.00	\$0.50- \$1.00	\$3.05- \$4.00
60	5.10- 6.00	0.50- 1.00	5.60- 7.00
120	10.20- 12.00	0.50- 1.00	10.70- 13.00
240	20.40- 24.00	0.50- 1.00	20.90- 25.00

Table 9. Cost per Acre Range of Custom Anhydrous Ammonia Application

Custom Rate: \$1.00 to \$2.00 per acre

Anhydrous Ammonia Cost: \$0.0425 to \$0.0550 per lb nitrogen

Application Rate per Acre	Fertilizer Cost	Custom Rate	Total Cost	Percent Savings by Applying NH_3 Rather than NH_4NO_3
30 lb	\$1.28- \$1.65	\$1.00- \$2.00	\$2.28- \$3.65	25.2- 8.8
60	2.55- 3.30	1.00- 2.00	3.55- 5.30	36.6- 24.3
120	5.10- 6.60	1.00- 2.00	6.10- 8.60	43.0- 33.8
240	10.20- 13.20	1.00- 2.00	11.20- 15.20	46.4- 39.2

ammonium nitrate are graphed in Figures 18 and 19. Depending on fertilizer cost and custom rates, custom application of anhydrous ammonia rather than ammonium nitrate produces savings if the nitrogen application rate is greater than 11.8 to 22.2 lb per acre (refer to Figure 19).

Machinery Management and Costs of Ownership

Machinery costs include charges for ownership and operation (3). Ownership costs are called fixed costs because they are independent of use. Fixed costs include depreciation, interest on investment, sales and property taxes, housing, and insurance. Costs of operation increase with use. These are variable costs which include repair and maintenance, lubrication, fuel, oil, labor, and fertilizer.

A simple cost approximation method uses straight-line depreciation (22). All annual fixed costs are calculated as a constant amount for each year of the implement's life. These are included in an annual fixed cost percentage, FC %, of the purchase price. For example, let salvage value, S, equal 10 percent of the purchase price, P, at the end of a 10 year service life, L.

$$\text{Annual depreciation} = \frac{P - S}{L} = \frac{P - 0.10\,P}{10} = 0.09\,P \text{ per year.}$$

Annual interest on the investment is estimated as an annual interest charge on the average machine investment over its life.

$$\text{Annual interest on investment} = \left(\frac{P + S}{2}\right)i = \left(\frac{P + 0.10\,P}{2}\right)(0.08)$$

$$= 0.044\,P.$$

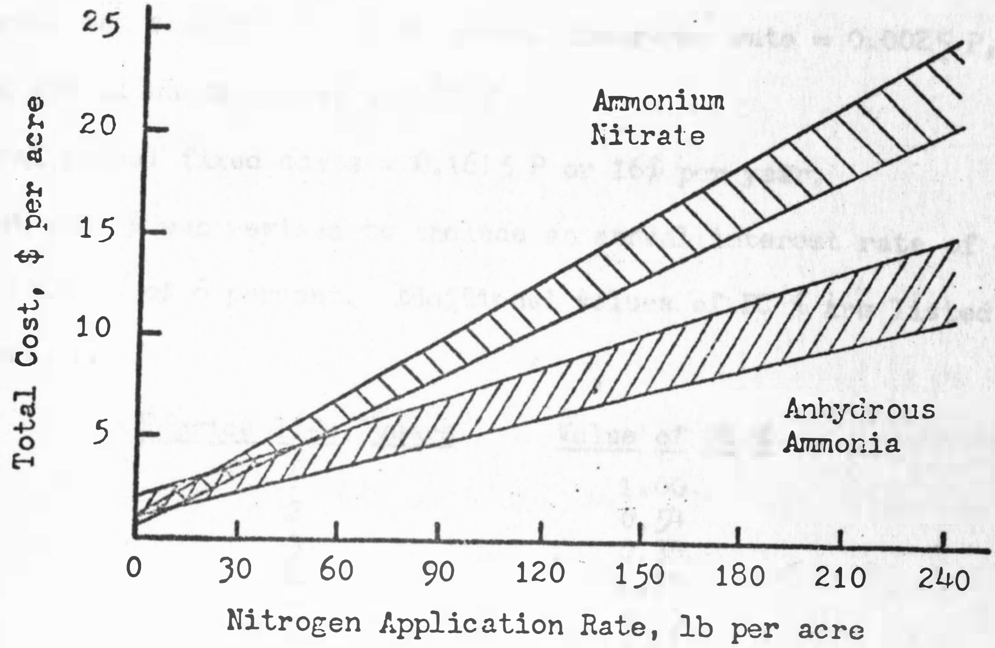

Figure 18. Cost Comparison of Custom Application of Anhydrous Ammonia and Ammonium Nitrate

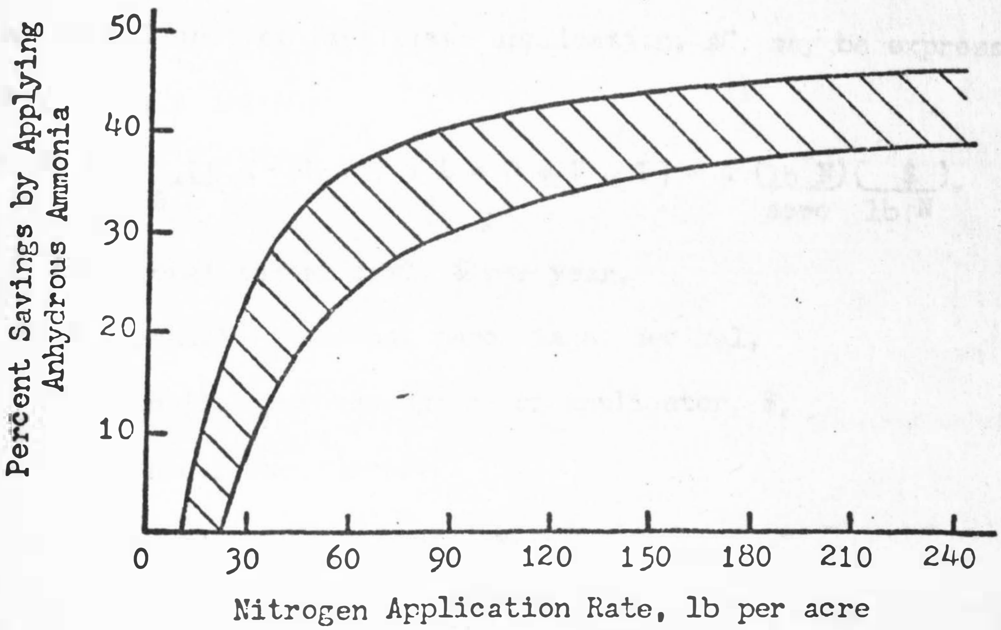

Figure 19. Percent Savings by Custom Application of Anhydrous Ammonia Rather than Ammonium Nitrate

Annual tax charge = 0.015 P, annual insurance rate = 0.0025 P, and annual shelter cost = 0.01 P.

Total annual fixed costs = 0.1615 P or 16% per year.

Hunt's FC % was revised to include an annual interest rate of 8 percent instead of 6 percent. Additional values of FC % are listed as follows:

Service life, years	Value of FC %
1	1.00
2	0.54
3	0.38
4	0.30
5	0.25
6	0.22
7	0.20
8	0.18
9	0.17
10	0.16
11	0.15
12	0.14
15	0.12
20	0.10

The total annual cost of fertilizer application, AC, may be expressed by the following equation:

$$AC = (FC\ \%)\ P + \frac{8.25\ A}{S\ w\ e}\left[RM\ (P) + L + O + F + T\right] + A\left(\frac{lb\ N}{acre}\right)\left(\frac{\$}{lb\ N}\right),$$

where AC = total annual cost, \$ per year,

FC % = annual fixed cost percentage, decimal,

P = initial purchase price of applicator, \$,

A = annual use, acres,

S = forward speed, mph,

w = effective width of machine, ft,

e = field efficiency, decimal,

RM = repair and maintenance factor, decimal of P per hr,

L = labor rate, \$ per hr,

O = oil cost, \$ per hr,

F = fuel cost, \$ per hr, and

T = tractor rent, \$ per hr.

Field efficiency is a measure of the relative productivity of a machine under field conditions (3). Field efficiency is determined by field and machine operating characteristics, the operator's capability and operating technique, time losses, and failure to use the total machine width. Common time losses include turning and idle travel, handling materials, cleaning clogged equipment, adjusting the machine, lubricating, and refueling. Typical speed and field efficiency ranges for anhydrous ammonia applicators and pull type fertilizer spreaders are 3 to 5 mph and 60 to 75 percent (3).

Total repairs during the estimated 1200 hr wear out life of fertilizer equipment equals 120 percent of the list price (3); thus, repair and maintenance hourly cost equals 0.001 P. It was assumed that initial purchase price equals list price for this part of the analysis.

Annual costs of fertilizing with a given granular spreader and resulting prices allowable for purchasing anhydrous ammonia equipment of equivalent width and annual cost were calculated for comparison with the assumptions described in the following paragraphs.

Coefficients of rolling resistance for pneumatic tires on bluegrass pastures vary from 0.04 for tires of 62-in. outside diameter and 40 psi inflation pressure to 0.06 for 25-in. diameter and 10 psi inflation pressure (2, 3).

The ratio of drawbar horsepower to power-take-off horsepower, $\frac{DBHP}{PTOHP}$ or tractive efficiency for tractors, (includes drive-wheel slippage, field conditions, tractor rolling resistance, and drive-train friction losses) for firm, untilled fields is 0.60 for light loads with pull less than or equal to 10 percent of tractor weight, 0.75 for medium drawbar loads, and 0.80 for heavy loads without excessive wheel slippage (2, 22).

A common draft requirement for anhydrous ammonia application, including rolling resistance of tractor and applicator, is 420 lb per knife as stated in the literature (3, 5). This draft requirement is probably for tilled soil conditions since the overall draft mean of the grassland tests described previously was about 500 lb per knife not including rolling resistance. The 500-lb draft requirement per knife was used in this analysis.

A cost analysis was made for a 12-ft granular spreader with maximum weight of 2000 lb and price of $550. The use of a 50-maximum-PTOHP, gasoline tractor was considered for this analysis. Tractor rental of $3.00 per hr was assumed for tractor cost (49). A 12-ft anhydrous ammonia applicator with 8 knives spaced at 18 in. was selected for comparison. Applicator and anhydrous ammonia vertical force reaction on the wheels was estimated as 5000 lb. An 80-maximum-PTOHP, gasoline tractor costing $4.00 per hr was assumed to power the anhydrous ammonia applicator (49).

$$\text{Total draft} = (500 \text{ lb/knife})(8 \text{ knives}) + (5000 \text{ lb})(0.05)$$

$$= 4250 \text{ lb.}$$

$$\text{DBHP at 4 mph} = \frac{(4250)(4)}{375} = 45.33 \text{ HP.}$$

$$\text{Equivalent PTOHP} = \frac{45.33}{0.80} = 56.67 \text{ HP.}$$

$$\text{Loading percent} = \frac{(56.67)(100)}{80} = 70.8\%.$$

Gasoline power conversion = 10 horsepower-hours per gallon (2).

$$(56.67 \text{ HP})\left(\frac{1 \text{ gallon}}{10 \text{ HP-HR}}\right) = 5.67 \text{ gallons per hr.}$$

Hourly fuel cost at $0.20 per gallon = $1.13 per hr.

Fuel consumption at 5 mph was calculated as 6.4 gallons per hr or $1.28 per hr for anhydrous ammonia application. The 50-HP tractor pulling the granular spreader consumes 2.2 gallons per hour or $0.45 per hr at 4 mph, and gasoline consumption at 5 mph was calculated as 2.5 gallons per hr or $0.50 per hour. Typical oil cost is $0.03 per hr (23), and the labor rate assumed was $1.60 per hour.

Fertilizer application at various rates and field efficiencies, e, was considered: 30 lb nitrogen per acre, e = 0.75; 60 lb nitrogen per acre, e = 0.70; 120 lb nitrogen per acre, e = 0.65; and 240 lb nitrogen per acre, e = 0.60. The decrease in field efficiency with increase in application reflects the time loss from handling fertilizer. Anhydrous ammonia cost of 5 1/4 cents per lb of nitrogen and ammonium nitrate cost of 9 1/2 cents per lb of nitrogen were assumed.

Various applicator service lives were used for different annual acreages to limit total use to less than 1200 hours. A 20-year service life was assumed for the lower annual fertilized acreages since an applicator would probably become obsolete after that time period.

The allowable prices for anhydrous ammonia equipment equalling corresponding annual costs for ammonium nitrate application in Tables 10 and 11 indicate that considerable savings may be made by applying anhydrous ammonia as total annual fertilized acreage and nitrogen requirements per acre increase.

Subjected to assigned numerical values for the variables, the annual cost equation allows the analysis of only one machine or situation at a time. The use of the annual cost equation has been expanded into a machinery selection method (22). Purchase price, repair and maintenance, fuel, and oil variables of the annual cost equation are changed to prices on a per ft width basis. The machine size of minimum annual cost is obtained by differentiating the annual cost equation with respect to width, setting the expression equal to zero, and solving for the optimum width. Such assumptions that costs of several sizes of machines may be represented by a cost per ft width basis and that cost of tractor use is a function of time only and independent of implement size may be challenged. The minimization method of machinery selection, therefore, will not be used in this analysis of fertilizer application equipment.

Table 10. Annual Cost of Ammonium Nitrate Application at 4 mph with a 12-ft Spreader and Amount Allowable to Spend for Anhydrous Ammonia Equipment of Equivalent Width and Total Annual Cost

4 mph	50 Acres per Year 20-Year Service Life			100 Acres per Year 20-Year Service Life		
Nitrogen Application Rate per Acre	Hours per Year	Annual Cost of NH_4NO_3 Application	Amount Allowable to Spend for NH_3 Equip.	Hours per Year	Annual Cost of NH_4NO_3 Application	Amount Allowable to Spend for NH_3 Equip.
30 lb	11.5	$260	$960	22.9	$470	$1,310
60	12.3	410	1,530	24.6	760	2,350
120	13.2	700	2,680	26.4	1,340	4,120
240	14.3	1,280	4,990	28.6	2,500	8,020
	200 Acres per Year 20-Year Service Life			400 Acres per Year 10-Year Service Life		
30	45.8	880	1,720	91.7	1,740	1,980
60	49.1	1,470	3,400	98.2	2,920	3,840
120	52.9	2,630	6,770	105.8	5,240	7,440
240	57.3	4,940	12,690	114.6	9,850	14,960
	800 Acres per Year 5-Year Service Life			1600 Acres per Year 2-Year Service Life		
30	183.3	3,450	2,210	366.7	6,750	2,150
60	196.4	5,800	4,350	392.8	13,840	6,610
120	211.5	10,450	8,650	423.1	20,920	8,320
240	229.2	19,670	16,750	458.3	39,360	16,100

Table 11. Annual Cost of Ammonium Nitrate Application at 5 mph with a 12-ft Spreader and Amount Allowable to Spend for Anhydrous Ammonia Equipment of Equivalent Width and Total Annual Cost

5 mph	50 Acres per Year 20-Year Service Life			100 Acres per Year 20-Year Service Life		
Nitrogen Application Rate per Acre	Hours per Year	Annual Cost of NH_4NO_3 Application	Amount Allowable to Spend for NH_3 Equip.	Hours per Year	Annual Cost of NH_4NO_3 Application	Amount Allowable to Spend for NH_3 Equip.
30 lb	9.2	$250	$980	18.3	$440	$1,310
60	9.8	400	1,550	19.6	740	2,380
120	10.6	690	2,700	21.2	1,320	4,490
240	11.5	1,260	5,010	22.9	2,470	8,720
	200 Acres per Year 20-Year Service Life			400 Acres per Year 12-Year Service Life		
30	36.7	830	1,890	73.3	1,630	2,370
60	39.3	1,420	3,690	78.6	2,800	4,550
120	42.3	2,580	7,310	84.6	5,120	9,150
240	45.8	4,880	13,260	91.7	9,720	17,580
	800 Acres per Year 6-Year Service Life			1600 Acres per Year 3-Year Service Life		
30	146.7	3,230	2,600	293.3	6,440	2,820
60	157.1	5,570	5,180	314.8	11,110	5,660
120	169.2	10,200	10,240	338.5	20,370	11,040
240	183.3	19,400	20,140	366.7	38,770	21,440

Straight-line depreciation is a convenient bookkeeping procedure for tax purposes, but the actual remaining farm value, RFV, of farm machinery is best reflected by a declining-balance depreciation method (3, 5). This is a yearly value reduction by a constant percentage of the remaining value. Remaining farm value is approximated as a percentage of the list price for the year, N in question as follows (3):

Tractors	$RFV = 0.68(\text{List Price})(0.920)^N$.
Fertilizer Application Equipment	$RFV = 0.60(\text{List Price})(0.885)^N$.

First year depreciation equals purchase price minus the RFV figure for N = 1. Other fixed costs may be estimated by the following rates (3):

Item	Annual Charge Percent of RFV
Interest	8.0%
Taxes	2.0
Housing	1.5
Insurance	0.5
Total	12.0%

Total life cost of these items is estimated as 6 percent of the list price (3). These rates for taxes, housing, and insurance are larger than those figured from straight-line depreciation of the previous cost analysis. Remaining values for straight-line depreciation are greater than the corresponding declining-balance depreciation remaining value for a given year.

The accumulated repair and maintenance costs of machinery at any age less than or equal to wear out life can be estimated by equations developed from machinery cost record surveys (3).

Tractor, 2-wheel drive	$TAR = 0.120(\text{List Price})(X)^{1.5}$,
Fertilizer Application Equipment	$TAR = 0.191(\text{List Price})(X)^{1.4}$,

where TAR = total accumulated repair cost, and

X = 100 times the ratio of accumulated hours of use to the wear out life.

Tractor wear out life is assumed as 12,000 hours. Wear out life for fertilizer application equipment is estimated as 1200 hours. Total repair costs during the wear out life of 2-wheel drive tractors and fertilizer application equipment totals 120 percent of the list price (3).

A Fortran computer program for average accumulated fixed costs and repair and maintenance costs has been developed with the help of the agricultural engineering staff (5). The computer program gives implement average costs per hr of operation per \$1000 list price for 25 hr per year increments to 500 hr annual usage to 15 years in age. It was assumed that the machine was purchased for 10 percent less than list price (5). Variable costs of fuel, oil, labor, and fertilizer were not included in the program. Program details are listed in Appendix D. The fertilizer applicator output is shown in Figure 20. Two-wheel-drive tractor fixed and repair and maintenance costs are contained in Figure 21.

ANHYDROUS AMMONIA APPLICATOR OR FERTILIZER SPREADER

DEP1	DEP2	TAX INS SHELT	INTEREST RATE	REPAIR 1	REPAIR 2	LIFE HOURS
0.885	0.60000	0.040	0.080	0.00191	1.40	1200.0

CUMULATIVE AVERAGE FIXED AND R&M COSTS PER HOUR OF OPERATION IN DOLLARS PER 1000 DOLLAR LIST PRICE OF IMPLEMENT

	AGE IN YEARS														
HRS. PER YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
25.0	19.29	12.32	9.83	8.47	7.58	6.92	6.41	5.99	5.64	5.34	5.07	4.84	4.63	4.44	4.27
50.0	9.82	6.39	5.19	4.54	4.12	3.82	3.59	3.40	3.24	3.11	2.99	2.89	2.80	2.72	2.65
75.0	6.69	4.45	3.68	3.28	3.02	2.84	2.70	2.60	2.51	2.43	2.37	2.32	2.27	2.23	2.19
100.0	5.14	3.50	2.95	2.67	2.50	2.38	2.30	2.23	2.18	2.13	2.10	2.07	2.05		
125.0	4.22	2.94	2.53	2.33	2.21	2.13	2.07	2.03	2.00	1.98					
150.0	3.62	2.58	2.26	2.11	2.05	1.98	1.94	1.92	1.91						
175.0	3.19	2.33	2.08	1.97	1.91	1.88	1.86								
200.0	2.88	2.15	1.95	1.87	1.83	1.82	1.81								
225.0	2.63	2.02	1.85	1.80	1.78	1.77									
250.0	2.44	1.91	1.78	1.74	1.74										
275.0	2.29	1.83	1.73	1.71	1.71										
300.0	2.17	1.76	1.69	1.68	1.70										
325.0	2.06	1.71	1.65	1.66											
350.0	1.98	1.67	1.63	1.65											
375.0	1.90	1.63	1.61	1.64											
400.0	1.84	1.61	1.60	1.63											
425.0	1.79	1.58	1.59												
450.0	1.74	1.56	1.58												
475.0	1.70	1.55	1.58												
500.0	1.66	1.54	1.57												

Figure 20. Fixed Costs and Repair and Maintenance Costs of Fertilizer Application Equipment

TRACTOR, 2 WHEEL DRIVE

DEP1	DEP2	TAX INS SHELT	INTEREST RATE	REPAIR 1	REPAIR 2	LIFE HOURS
0.920	0.68000	0.040	0.080	0.00120	1.50	12000.0

CUMULATIVE AVERAGE FIXED AND R&M COSTS PER HOUR OF OPERATION IN DOLLARS PER 1000 DOLLAR LIST PRICE OF TRACTOR

	AGE IN YEARS														
HRS. PER YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
25.0	15.30	10.16	8.31	7.29	6.62	6.12	5.72	5.38	5.10	4.85	4.62	4.42	4.24	4.07	3.91
50.0	7.65	5.08	4.16	3.66	3.32	3.07	2.87	2.70	2.56	2.44	2.33	2.22	2.13	2.05	1.97
75.0	5.11	3.39	2.78	2.44	2.22	2.05	1.92	1.81	1.72	1.64	1.56	1.50	1.44	1.38	1.33
100.0	3.83	2.55	2.09	1.84	1.67	1.55	1.45	1.37	1.30	1.24	1.18	1.13	1.09	1.05	1.01
125.0	3.07	2.04	1.68	1.48	1.34	1.25	1.17	1.10	1.05	1.00	0.96	0.92	0.88	0.85	0.82
150.0	2.56	1.71	1.40	1.24	1.13	1.04	0.98	0.93	0.88	0.84	0.80	0.77	0.74	0.72	0.69
175.0	2.20	1.47	1.21	1.06	0.97	0.90	0.85	0.80	0.76	0.73	0.70	0.67	0.65	0.62	0.60
200.0	1.92	1.29	1.06	0.94	0.85	0.79	0.75	0.71	0.67	0.64	0.62	0.60	0.57	0.55	0.54
225.0	1.71	1.15	0.95	0.84	0.76	0.71	0.67	0.64	0.61	0.58	0.56	0.54	0.52	0.50	0.49
250.0	1.54	1.04	0.86	0.76	0.69	0.65	0.61	0.58	0.55	0.53	0.51	0.49	0.47	0.46	0.45
275.0	1.41	0.94	0.78	0.69	0.63	0.59	0.56	0.53	0.51	0.49	0.47	0.45	0.44	0.42	0.41
300.0	1.29	0.87	0.72	0.64	0.59	0.55	0.52	0.49	0.47	0.45	0.44	0.42	0.41	0.40	0.39
325.0	1.19	0.80	0.67	0.59	0.55	0.51	0.48	0.46	0.44	0.42	0.41	0.40	0.38	0.37	0.36
350.0	1.11	0.75	0.62	0.55	0.51	0.48	0.45	0.43	0.41	0.40	0.39	0.37	0.36	0.35	0.34
375.0	1.04	0.70	0.58	0.52	0.48	0.45	0.43	0.41	0.39	0.38	0.37	0.35	0.35	0.34	0.33
400.0	0.97	0.66	0.55	0.49	0.45	0.43	0.40	0.39	0.37	0.36	0.35	0.34	0.33	0.32	0.31
425.0	0.92	0.62	0.52	0.47	0.43	0.41	0.39	0.37	0.36	0.34	0.33	0.32	0.32	0.31	0.30
450.0	0.87	0.59	0.49	0.44	0.41	0.39	0.37	0.35	0.34	0.33	0.32	0.31	0.30	0.30	0.29
475.0	0.82	0.56	0.47	0.42	0.39	0.37	0.35	0.34	0.33	0.32	0.31	0.30	0.29	0.29	0.28
500.0	0.79	0.54	0.45	0.41	0.38	0.36	0.34	0.33	0.32	0.31	0.30	0.29	0.28	0.28	0.27
525.0	0.75	0.51	0.43	0.39	0.36	0.34	0.33	0.31	0.30	0.30	0.29	0.28	0.28	0.27	0.27
550.0	0.72	0.49	0.41	0.37	0.35	0.33	0.32	0.30	0.30	0.29	0.28	0.27	0.27	0.26	0.26
575.0	0.69	0.47	0.40	0.36	0.34	0.32	0.31	0.30	0.29	0.28	0.27	0.27	0.26	0.26	0.25
600.0	0.66	0.45	0.38	0.35	0.33	0.31	0.30	0.29	0.28	0.27	0.27	0.26	0.26	0.25	0.25
625.0	0.63	0.44	0.37	0.34	0.32	0.30	0.29	0.28	0.27	0.27	0.26	0.26	0.25	0.25	0.24
650.0	0.61	0.42	0.36	0.33	0.31	0.29	0.28	0.27	0.27	0.26	0.25	0.25	0.25	0.24	0.24
675.0	0.59	0.41	0.35	0.32	0.30	0.28	0.27	0.27	0.26	0.25	0.25	0.25	0.24	0.24	0.24
700.0	0.57	0.40	0.34	0.31	0.29	0.28	0.27	0.26	0.25	0.25	0.24	0.24	0.24	0.23	0.23
725.0	0.55	0.38	0.33	0.30	0.28	0.27	0.26	0.25	0.25	0.24	0.24	0.24	0.23	0.23	0.23
750.0	0.53	0.37	0.32	0.29	0.28	0.26	0.26	0.25	0.24	0.24	0.24	0.23	0.23	0.23	0.23
775.0	0.52	0.36	0.31	0.29	0.27	0.26	0.25	0.25	0.24	0.24	0.23	0.23	0.23	0.23	0.22
800.0	0.50	0.35	0.30	0.28	0.26	0.25	0.25	0.24	0.24	0.23	0.23	0.23	0.22	0.22	0.22
825.0	0.49	0.34	0.30	0.27	0.26	0.25	0.24	0.24	0.23	0.23	0.23	0.22	0.22	0.22	0.22
850.0	0.48	0.34	0.29	0.27	0.25	0.24	0.24	0.23	0.23	0.23	0.22	0.22	0.22	0.22	0.22
875.0	0.46	0.33	0.28	0.26	0.25	0.24	0.23	0.23	0.23	0.22	0.22	0.22	0.22	0.22	
900.0	0.45	0.32	0.28	0.26	0.24	0.24	0.23	0.23	0.22	0.22	0.22	0.22	0.22	0.21	
925.0	0.44	0.31	0.27	0.25	0.24	0.23	0.23	0.22	0.22	0.22	0.22	0.22	0.21		
950.0	0.43	0.31	0.27	0.25	0.24	0.23	0.22	0.22	0.22	0.22	0.21	0.21	0.21		
975.0	0.42	0.30	0.26	0.24	0.23	0.23	0.22	0.22	0.22	0.21	0.21	0.21	0.21		
1000.0	0.41	0.29	0.26	0.24	0.23	0.22	0.22	0.22	0.21	0.21	0.21	0.21	0.21		

Figure 21. Fixed Costs and Repair and Maintenance Costs of Tractors with 2-Wheel Drive

Cumulative average costs per acre for ammonium nitrate application at 4 mph with 12-ft spreaders costing $500 and $600 were calculated using the computer program (refer to Table 12). Annual costs for a $550, 12-ft spreader and the amount allowable to purchase anhydrous ammonia application equipment at an equivalent annual cost are included in Table 13. The list prices of the tractors were assumed as $5000 and $8000 respectively for the 50-HP and 80-HP gasoline tractors. Tractor costs were based on 600 hr annual use averaged over 10 years.

Many of the ammonium nitrate application annual cost figures over a 5-year average in Table 13 are lower than those calculated by the annual cost equation for a longer time period in Table 10. Although a larger fixed cost factor exists for the 5-year average from the declining-balance depreciation method, the totals of Table 10 include the large tractor rental costs of the annual cost equation. The linear repair and maintenance cost factor of the annual cost equation adds more cost per hr prior to wear out than the more accurate total accumulated repair equation adds in Table 13. The resulting amount allowable to spend for anhydrous ammonia equipment with equivalent annual cost in Table 13 are smaller than those in Table 10 for nitrogen application on low annual acreages but larger for high fertilized acreages. The reasons include the varying cost factors described above and different time periods used for the two methods.

Table 12. Cost of Applying Ammonium Nitrate with a 12-ft Spreader; Fixed and Repair and Maintenance Costs were Calculated by the Computer Program

4 mph	Nitrogen Application Rate per Acre	Annual Fertilized Acreage 100	200	400	800	1600 3 Year Average
		Cumulative Average Cost per Acre Over 5 Years				
$600, 12-ft Spreader	30 lb	$4.78	$4.28	$4.00	$3.89	$3.86
	60	7.66	7.16	6.92	6.81	6.78
	120	13.93	13.39	13.15	13.04	13.01
	240	24.91	24.35	24.10	24.00	23.97
$500, 12-ft Spreader	30	4.59	4.17	3.94	3.85	3.82
	60	7.48	7.06	6.85	6.77	6.74
	120	13.74	13.29	13.08	13.01	12.97
	240	24.70	24.24	24.03	23.94	23.92

Table 13. Total Annual Cost of Ammonium Nitrate Application and the Amount Allowable to Spend for Anhydrous Ammonia Equipment of Equivalent Width and Annual Cost by Using the Computer Program

	Nitrogen Application Rate per Acre	Annual Fertilized Acreage 100	200	400	800	1600
		5-Year Average				3-Year Average
Total Annual Cost for Operating a $550, 12-ft Spreader	30 lb	$470	$850	$1,590	$3,100	$6,140
	60	760	1,420	2,750	5,430	10,810
	120	1,380	2,680	5,240	10,420	20,790
	240	2,480	4,860	9,620	19,180	38,310
Maximum Allowable Price for 12-ft Anhydrous Ammonia Equipment with Equivalent Annual Cost	30	1,040	1,420	2,080	2,720	3,070
	60	1,550	2,340	3,530	4,670	5,180
	120	3,190	5,440	8,580	11,340	12,820
	240	5,330	9,450	15,070	19,650	21,950

Nevertheless, as nitrogen application per acre and annual fertilized acreage increase, the amount allowable to spend for anhydrous ammonia equipment increases when total annual costs are equal to the annual cost of spreading granular ammonium nitrate. The allowable prices of anhydrous ammonia application equipment for the higher nitrogen application rates are much higher than what would be spent for the equipment. This indicates that savings may be made by applying anhydrous ammonia rather than ammonium nitrate.

Application by Applicator Rental

Fertilizer applicator rental with a cost per acre charge is probably the most common method of applying fertilizer, excluding application simultaneously with planting. The farmer furnishes his own tractor, fuel, and labor. A typical rate for granular spreaders in South Dakota is $0.25 per acre. Anhydrous ammonia applicator and nurse tank rental is commonly $0.50 per acre (7).

Some rental agencies charge a rental price per ton instead of a per-acre charge for granular spreaders (36). Another exception to the common rental charge per acre is that the anhydrous ammonia applicator and nurse tank use is sometimes included in the selling price of anhydrous ammonia.

Table 14 includes costs per acre of anhydrous ammonia application at 4 and 5 mph based on applicator rental of $0.50 per acre. The same 12-ft applicator draft requirement and 80-HP tractor costs from the computer program were used. Fuel consumption at 5 mph was $0.12 per hr more than the consumption at 4 mph. Nevertheless, when all costs were considered the net effect is a higher cost per acre at 4 mph because of the longer time required.

Better soil sealing to prevent anhydrous ammonia loss can be attained in moist conditions. Also, the moisture readily ionizes the anhydrous ammonia, and the ammonium ions are adsorbed by clay particles and organic matter. Applicator draft requirements increase as soil moisture decreases. From the draft data, the mean draft for the first two soil moisture conditions was 430 lb per knife assuming no draft difference with speed. The mean draft for the very dry condition was 600 lb. This would increase the loading of the 80-HP tractor from 66 percent to 84 percent. Gasoline consumption would increase from 5.4 gallons per hr to 6.2 gallons per hr (3) or from $1.08 per hr to $1.24 per hr if the price was $0.20 per gallon. This fuel cost difference caused an increase of only $0.04 per acre as shown in Table 15.

Rental costs per acre were also calculated for a 5-ton granular spreader (Table 16). A 40-ft broadcast width was assumed. Maximum draft was 625 lb assuming a maximum total weight of 12,500 lb and rolling resistance coefficient of 0.05 (2, 3). The 50-HP tractor was 22 percent loaded at 4 mph and 28 percent loaded at 5 mph. Respective fuel consumption and costs became 2.6 gallons per hr and $0.52 per hr, and 2.9 gallons per hr and $0.58 per hr. Applicator rental was assumed to be $0.25 per acre (7). The cost per acre decreased as speed increased from 4 to 5 mph, a similar characteristic of anhydrous ammonia application as shown in Table 14.

Table 14. Cost per Acre for Anhydrous Ammonia Application with a 12-ft Applicator Rental Rate of $0.50 per Acre

Nitrogen Application Rate per Acre	Acres per Hour	Cost per Acre at 4 mph	Acres per Hour	Cost per Acre at 5 mph
30 lb	4.37	$3.20	5.46	$2.71
60	4.06	5.18	5.10	4.33
120	3.79	8.10	4.72	7.53
240	3.48	14.51	4.37	13.90

Table 15. Cost per Acre Comparison of Anhydrous Ammonia Grassland Application on Two Soil Moisture Conditions

Nitrogen Application Rate per Acre	Moist Condition 430 lb Draft per Knife	Dry Condition 600 lb Draft per Knife
30 lb	$3.19	$3.23
60	5.17	5.21
120	8.09	8.13
240	14.50	14.54

Table 16. Cost per Acre for Ammonium Nitrate Application with a 5-ton Spreader Having a 40-ft Broadcast Width; Rental Rate = $0.25 per Acre

Nitrogen Application Rate per Acre	4 mph		5 mph	
	Acres per Hour	Cost per Acre	Acres per Hour	Cost per Acre
30 lb	14.54	$3.34	18.18	$3.30
60	13.58	6.21	16.67	6.16
120	12.60	12.23	15.75	11.88
240	11.64	23.35	14.55	23.29

In summary all the previously calculated figures were dependent upon specific assumptions, but they can be considered realistic. All calculated cost-per-acre figures were within the range of the custom-rate costs in Tables 3 and 4. The application cost of anhydrous ammonia is greater than that for ammonium nitrate, but the fertilizer price difference, favoring anhydrous ammonia over ammonium nitrate, produces a net effect of lower total cost for anhydrous ammonia fertilization. The price per lb of nitrogen for anhydrous ammonia is commonly over 40 percent less than the price for ammonium nitrate. Dollar savings by applying anhydrous ammonia will increase as the nitrogen application rate per acre and annual fertilized acreage increase. The effect of 1 lb of nitrogen from anhydrous ammonia may not be the same as the effect of 1 lb of nitrogen from ammonium nitrate. For example, full benefit of anhydrous ammonia is delayed for a period of time after application as described in the Review of Literature. Nevertheless, if anhydrous ammonia is less effective than an equal nitrogen rate of ammonium nitrate after nitrification, the operator could afford to apply a greater rate of anhydrous ammonia per acre to obtain comparable results.

PASTURE INTERSEEDING USING MODIFIED APPLICATORS

The 30° knife applicators were modified for use as interseeders (Figure 22). The purpose was to investigate the feasibility of interseeding grassland and to simultaneously apply fertilizer with a minimum of sod disturbance.

Equipment Additions for Interseeding

Sixteen-in. lengths of 1/4-in. pipe were welded to the rear of the closing-sweep shanks of four applicators (Figure 23). The pipe outlets were placed approximately 1/2 in. above the closing sweeps, and the pipe ends were slightly flattened and dressed with a grinding wheel to the approximate width of the 3/8-in. shanks. Thus, the inside outlet width was reduced to about 7/32 of an inch. The pipes were bent so that alfalfa seed could be metered through them onto the soil above the closing sweep. The four applicators were spaced for 24-in. rows.

A Gandy granular-chemical, row-crop applicator, Model 910-4W containing 4 outlets, was bracketed to the tool bar and centered behind the anhydrous ammonia tank. Hopper outlets were about 40 in. above ground level. Hopper capacity was about 0.4 bushel. A 16 1/2-in. steel Noble ground drive wheel drove the rotor by a detachable-link chain drive with a 5.15 to 1 speed reduction. One-half-in. inside diameter clear vinyl tubing guided the seeds from the hopper outlets to the applicators. The four, 24-in. row interseeder was

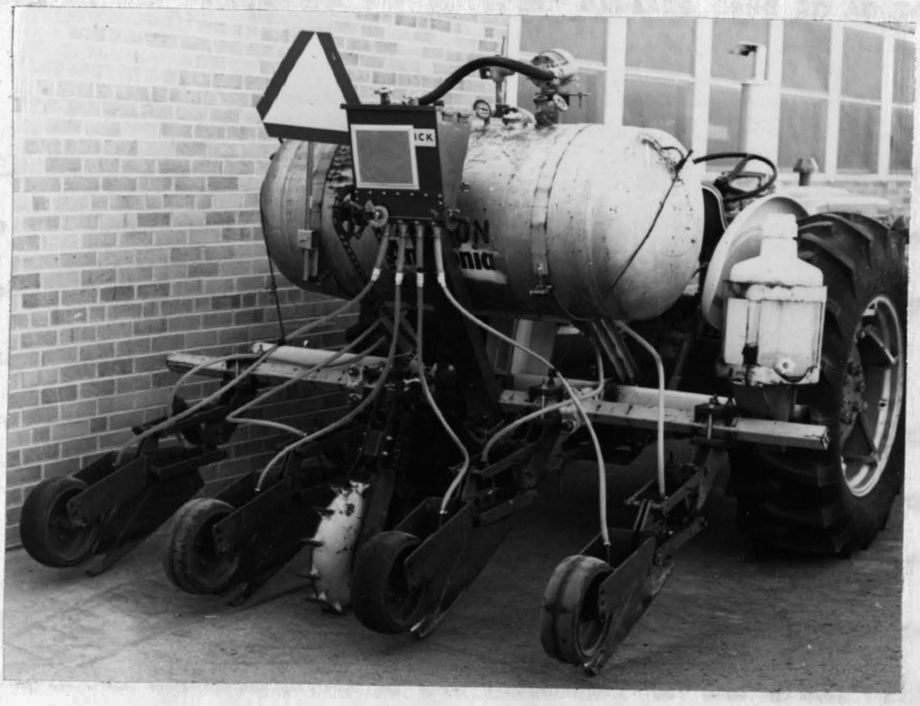

Figure 22. Equipment Modification for Interseeding

Figure 23. Seed Outlet of the Interseeder

calibrated in the laboratory for metering alfalfa seed in lb per acre at speeds of 3, 4, and 5 mph.

<u>Characteristics of Operation and Observations of Resulting Growth</u>

The initial interseeding with the modified applicators was performed on August 25, 1970, on about 3 acres of closely grazed native-grass pasture near Elkton, South Dakota. Soil conditions were very dry. Twenty-four-in. rows of alfalfa were seeded at the rate of 2 1/2 lb per acre while anhydrous ammonia was injected at approximate rates of 80, 160, 270, and 375 lb nitrogen per acre. Strips of 110 lb nitrogen per acre with interseeding alternated with interseeding and no anhydrous ammonia covered the remainder of the area. Knife penetration depth varied from 2 1/2 to 4 inches. At times the depth-control wheels did not contact the ground. A soil seal compacted by the closing sweep and presswheel above the point of anhydrous ammonia release was detected by forcing a thin, metal ruler into the knife slit and feeling it penetrate. Seed placement was near the soil surface, and some seeds were visible. The knives without coulters cut through taller grass in a slough. Trash did not collect ahead of the blades as occurred during a trial the following spring.

Very little alfalfa growth was observed by the end of September since seeds were lying in dry soil. At this time the anhydrous ammonia effect was just becoming visible by noting the brighter green strips along the knife slits.

No distinction among the anhydrous ammonia application rates could be made during observations on April 29, 1971, but the stimulated strips of grass had widened to about 12 inches. It appeared that some of the alfalfa seedlings which had germinated the previous fall had perished during the winter, but many new seedlings had recently started from seeds that did not germinate earlier. A few seeds were also visible in the knife slits and on the sod adjacent to the slits.

An additional area was interseeded on April 29, 1971, in the same pasture. Alfalfa was again interseeded at a 2 1/2 lb per acre rate with 0, 80, and 160 lb nitrogen per acre applications. Applicator depth varied between 3 and 4 in., and penetration was better than that observed during the fall interseeding. Dead grass occasionally collected ahead of the knives, and the tool bar had to be lifted to clear the blades.

An improvised liquid fertilizer application with interseeding was also made because there was an immediate opportunity of using a tractor equipped with a saddle tank and a sprayer pump. A solution of 12 gallons of 28 percent nitrogen and 6 gallons of 10-34-0 (total solution weight = 11 lb per gallon) was applied to 0.4 acre by placing the outlet hose from the sprayer pump into a fitting of the distribution manifold. Pump pressure was regulated as low as possible, and resulting application rates were about 110 lb nitrogen and 55 lb available phosphoric acid per acre.

By June 4 many new seedlings were observed, but there were fewer in the area of the high anhydrous ammonia application rate. Brown grass adjacent to the knife slits indicated some sod burn from the high rate of application. The alfalfa stand seemed to be the best where liquid fertilizer was applied. The grass was stimulated in about a 6-in. wide strip by anhydrous ammonia and liquid fertilizer. The dark-green strips had expanded to a 15-in. width in the fall applications. The fall-interseeded alfalfa stand was best where no anhydrous ammonia was applied.

Pasture growth was lush by mid July. The grass had not been grazed since the previous fall. Very little alfalfa growth was visible in the fertilized bands. The fertilized-alfalfa seedlings that were present were less than 3 in. tall and were heavily surrounded by the stimulated grass. The visible, fall fertilizer effect nearly covered the entire 24-in. row width at this time (Figure 24) compared with less than 1-ft wide stimulated strips for the spring fertilizer applications.

The best alfalfa growth was the fall interseeding without fertilizer application (Figure 25). Although the stand was sparse, some fall interseeded alfalfa was in bloom and about 12 in. tall. The interseeded-alfalfa population was the greatest in local areas where the cattle decreased the competition from surrounding vegetation by grazing the grass close to the soil the previous fall.

Figure 24. Anhydrous Ammonia Effect, Approximately 160 lb N per Acre in 24-in. Rows, in Native Pasture Eleven Months After Interseeding

Figure 25. Alfalfa Growth in 24-in. Rows in Native Pasture Eleven Months After Interseeding

RESULTS AND CONCLUSIONS

The following results and conclusions were obtained from this investigation:

1. The overall draft mean of the experimental applicators on an alfalfa-brome mixture was 500 lb per knife. The draft requirement of the driest soil condition was 600 lb per knife, 170 lb greater than that required for the other two soil moisture conditions.
2. The draft increased approximately 16 percent as speed increased from 3 to 6 mph for the forward-swept knife, but there was no significant draft increase with speed for the back-swept knives.
3. The forward-swept knife required an average vertical force of 60 lb to penetrate the sod as compared with the vertical, soil-penetrating force averages of 130 to 200 lb for the back-swept knives.
4. It was not possible in this study to determine if force differences on the back-swept applicators were caused by the knife angle or the coulter.
5. A coulter was required with the forward-swept knife to prevent the blade from raking sod and vegetation. When no coulters were used trash was most easily cut by the 30°, back-swept design. The most sod disturbance along the knife slit was from the forward-swept knife. The best knife-slit seal was formed by the closing sweeps and presswheels of the back-swept applicators.

6. The equipment and application costs of anhydrous ammonia are greater than those for ammonium nitrate; however, the substantial price difference of the two nitrogen sources, from 35 to 53 percent less per lb of nitrogen for anhydrous ammonia compared with ammonium nitrate for the examples considered, produces a net effect of a lower total cost per acre for anhydrous ammonia fertilization.
7. The best alfalfa plant population, interseeded by the modified knife applicators, was interseeded in the fall and grew in areas of no fertilizer application where cattle had reduced the competition from surrounding vegetation by grazing. But the stand of mature alfalfa plants was sparse. It appeared that competition from established vegetation was the primary factor that limited the growth of the knife-slit interseeded alfalfa.

SUMMARY

Much grassland acreage in the Upper Great Plains is not producing to full capacity. Nitrogen deficiency, insufficient moisture, and poor seasonal distribution of moisture are common causes. An economical method of grassland fertilization could promote more extensive pasture management and improved pasture production.

Experimental knife fertilizer applicators were analyzed for functional performance and the influence of selected factors on grassland draft requirements. Draft and vertical force data were recorded and analyzed for 5 experimental applicators for 3 speeds, 2 depths, and 3 moisture conditions. Soil moisture, soil shear, soil-to-metal adhesion and friction, and penetration resistance measurements were recorded to identify soil conditions. The overall draft mean was 500 lb per knife. The mean draft for the driest condition was 600 lb per knife compared with 430 lb averaged over the other two soil moisture conditions. The draft of the forward-swept knife increased with speed, but there was no significant draft increase with speed for the back-swept knives. The analyses of variance revealed several significant interactions which could not be explained. This limited the determination of how specific factors influenced the applicator forces.

The 30°, back-swept knives without coulters cut through trash better than the 45° design. The forward-swept knife required the least vertical force to penetrate the soil although a coulter was necessary to prevent sod and vegetation from plugging the system.

It left a rougher surface along the knife slit compared with the back-swept knives. The best soil seal in the knife slit was formed by the closing sweeps and presswheels of the back-swept knives.

Cost analyses were made of anhydrous ammonia and ammonium nitrate application. Costs per acre were computed for typical 1971 price ranges of custom rates and fertilizer costs. Fixed and variable costs were computed to obtain annual costs. A more accurate method for fixed and repair and maintenance costs was obtained by using a computer program. Total annual costs of ammonium nitrate application were calculated.

Allowable prices to spend for anhydrous ammonia equipment with equal total annual cost were then calculated. For large nitrogen application rates per acre, allowable anhydrous ammonia equipment prices were higher than what would be ordinarily be spent. This indicated that money could be saved by applying anhydrous ammonia rather than ammonium nitrate. The equipment and application costs of anhydrous ammonia are higher than those for ammonium nitrate, but the lower cost of the fertilizer, anhydrous ammonia, results in a lower total cost of anhydrous ammonia application.

The 30°, back-swept knives were modified and used as interseeders. Spring and fall alfalfa interseeding and fertilization in 24-in. rows were performed on native pasture. The fall interseeded alfalfa grew best but in areas where fertilizer was not applied and where the competition from surrounding grass was reduced by grazing. The stand of mature alfalfa was generally poor. Anhydrous ammonia stimulated the grass growth in nearly the entire row width after nine months.

SUGGESTIONS FOR FUTURE RESEARCH

This investigation gave indications of draft requirements, vertical soil-penetrating forces, and operating characteristics of experimental knife applicators on grassland. All tests were run on the same field of one soil type and one grass mixture. Tests on other grassland conditions could give more general conclusions. Keeping the variation of knife depth to a minimum was difficult. Thus, some inconsistent force data may have limited specific findings.

Several significant interactions from the analysis of variance could not be explained in this study. No definite conclusions about the influence of the coulter and angle of the back-swept knife on applicator forces could be made. Additional data from an experimental design concentrating on these factors is needed to determine how coulter and knife angle influence the applicator forces.

Time required to read the chart data by planimetering was lengthy. It might have been more beneficial if the number of factors had been reduced, for example, fewer knives and only one speed and one depth but more replications. More data could have been studied with an improved integration system.

Only a few cost examples of fertilization were presented because it is difficult to forsee the typical equipment and types of fertilization systems that may be used by most operators in the future. The cost analysis presented allows comparisons under the assumed conditions. Annual costs of particular situations may be calculated by using the more detailed cost analysis methods which were reviewed.

Further investigation of the way anhydrous ammonia influences grass growth under various conditions, such as rates and time of application, compared with the effects from other fertilizers may be desirable. If one fertilizer form gives a better response at a particular rate but costs more, possibly a higher application rate of the less expensive fertilizer could give comparable growth results with an equal expenditure or even savings.

Competition from surrounding vegetation appeared to be the limiting factor of the alfalfa growth in the native pasture interseeding with the modified applicators. If growth competition is a limiting factor, a device for the applicator knives could be developed to remove some sod along the knife slits. Only alfalfa was interseeded at one rate. The response of other interseeded grasses or legumes might have been different.

High rates and location of the fertilizer near the seed may have caused poor germination, poor seedling vigor, and poor survival of the interseeded alfalfa. If independent interseeding and fertilization operations give the best results, alternated rows of interseeding and fertilizing could give overall pasture improvement; however, the corresponding equipment design might be complex.

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APPENDIX A. Design of the Force Transducer

THE FORCE TRANSDUCER

The concept of an inexpensive, simple force transducer that could measure two force components and a moment was obtained from Cook and Rabinowicz (6). The resultant force in a plane and its line of action may be obtained from F_x, the horizontal force in the direction of tool travel; F_z, the vertical force; and M_y, the moment in the plane of these two forces. The transducer used to measure the applicator soil forces consisted of an aluminum alloy extended octagonal ring with twelve 1/4-in. electrical resistance strain gages (Figure 26). The strain gages were wired into three Wheatstone bridge circuits based on the work of Siemens (39).

The voltage output from each bridge was recorded by a two-channel oscillograph (Offner Type RS). Thus, only two of the three components could be recorded simultaneously. The transducer was calibrated by placing it in tension in a hydraulic testing machine (Soiltest Versa-tester Model AP-350). The calibration process revealed that an applied force in one direction yielded an effect of less than 2 percent of the known force in the other direction.

The design of the octagonal extended ring transducer is based on the analysis of the extended ring transducer (Figure 27). The octagonal design facilitates construction and strain gage application. The extended ring design gains stability to prevent the ring from rolling. Rotation at sections A and B is assumed to be negligible (6, 39).

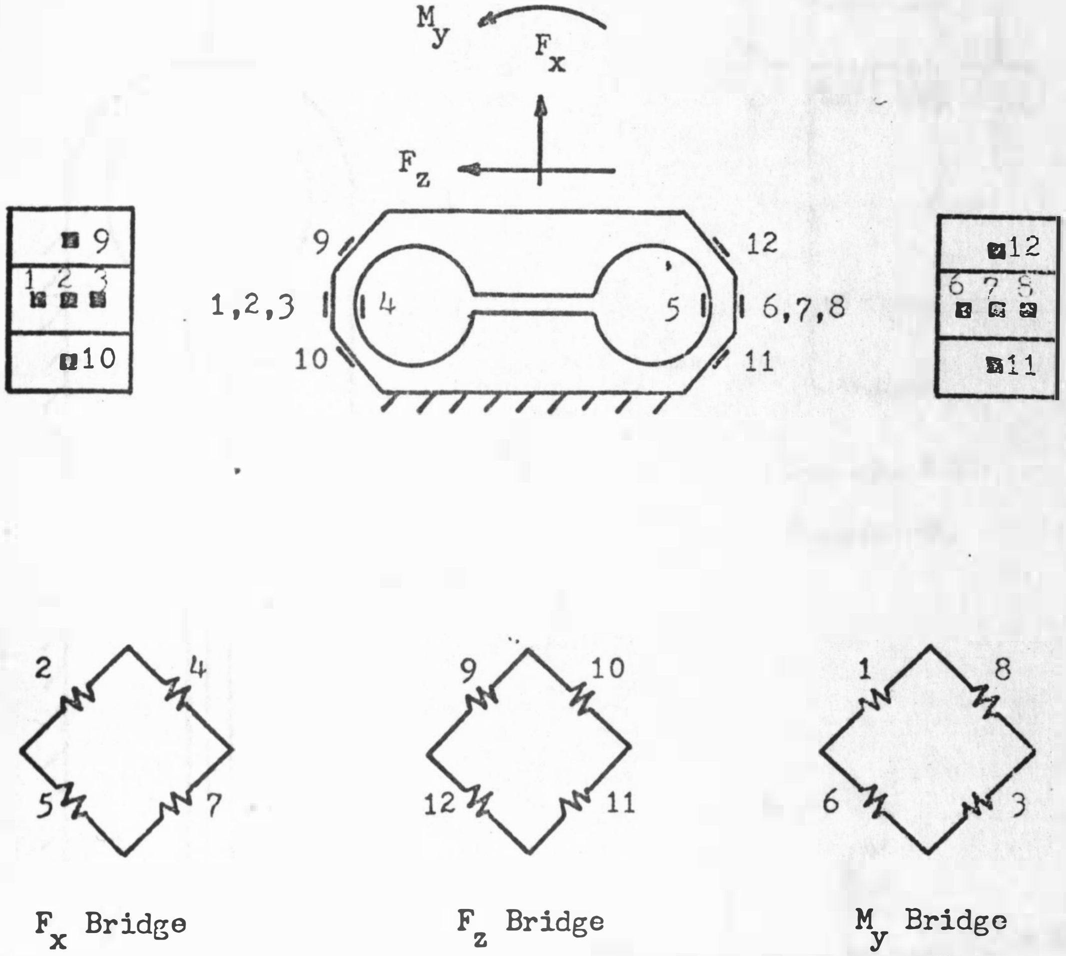

Figure 26. Force Transducer with Strain Gage Locations and Wheatstone Bridge Circuits

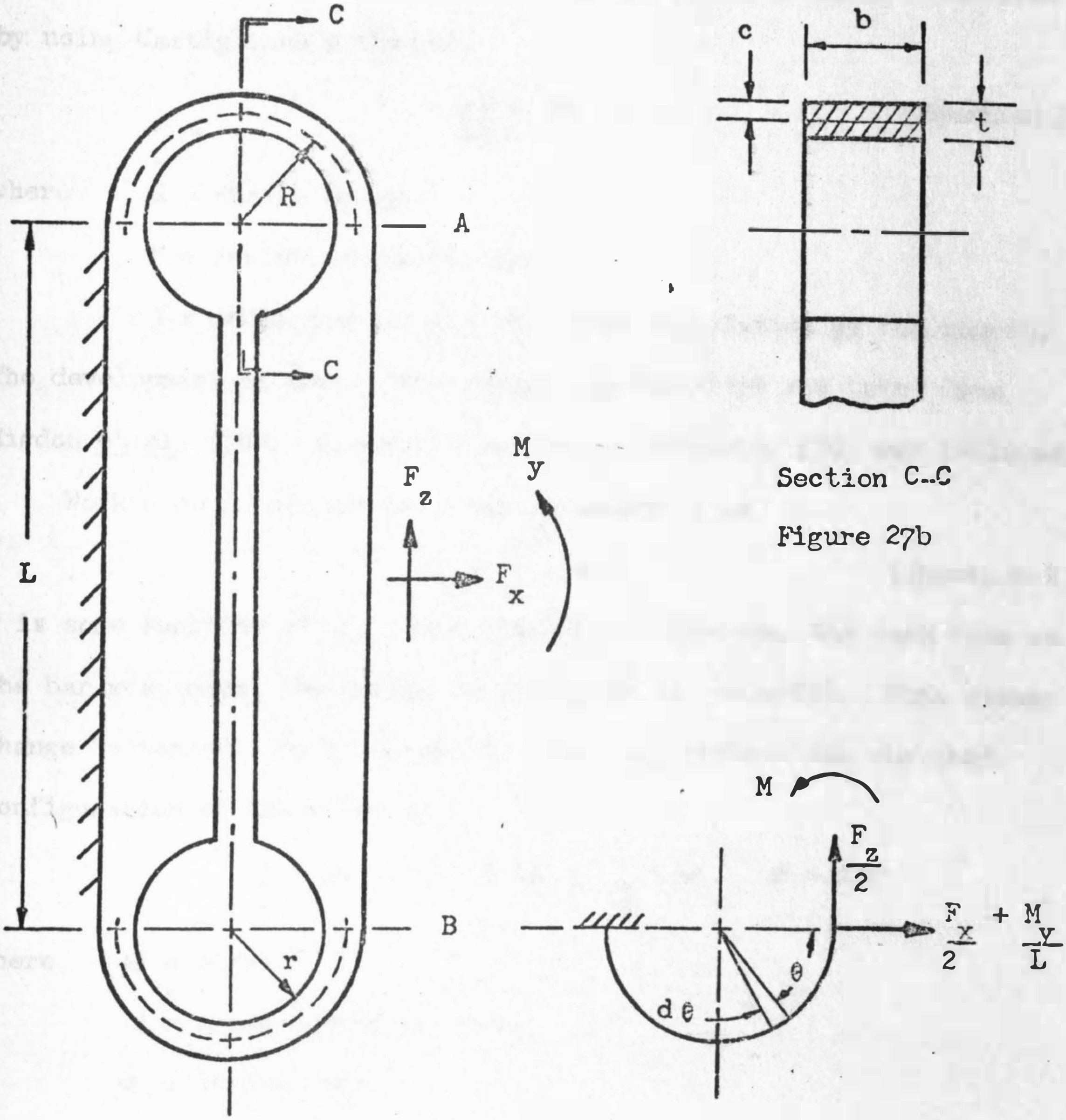

Figure 27a

Figure 27c

Figure 27. Free-Body Diagram of the Extended Ring Transducer

The expression for the bending moment at any section is derived by using Castigliano's theorem:

$$\frac{\partial U}{\partial M} = \Upsilon = 0 \qquad \text{(Equation 1)}$$

where U = strain energy,

M = resisting moment, and

Υ = deflection of the structure as affected by the moment.

The development of the strain energy relationships was taken from Higdon <u>et</u> <u>al</u>. (19). Siemens' theoretical procedure (39) was followed.

Work done in elongating a bar by amount δ is

$$W_k = \int_0^{\delta} P \, d\delta \, . \qquad \text{(Equation 2)}$$

P is some function of δ. From Clapeyron's theorem, the work done on the bar must equal the change in energy of the material. This energy change is termed strain energy, U, since it involves the strained configuration of the material.

$$\frac{\delta}{L} = \epsilon, \quad d\delta = L \, d\epsilon \; ; \; \frac{P}{A} = \sigma, \quad P = A\sigma$$

where ϵ = strain,

A = cross-sectional area,

σ = stress, and

L = original length.

$$W_k = U = \int_0^{\epsilon} A \sigma L \, d\epsilon = A L \int_0^{\epsilon} \sigma \, d\epsilon \qquad \text{(Equation 3)}$$

when the expressions for P and $d\delta$ are substituted in Equation 2. If Hooke's law applies, then $\epsilon = \frac{\sigma}{E}$; and $d\epsilon = \frac{d\sigma}{E}$ where E = modulus of elasticity. Then, from Equation 3

$$U = \frac{A\,L}{E}\int_0^{\sigma} \sigma d\sigma = \frac{A\,L\sigma^2}{2\,E}.$$

The quantity $\frac{\sigma^2}{2\,E}$ is elastic strain energy, u, per unit volume for a given σ.

Therefore, total strain energy $U = \int_V \frac{\sigma^2}{2\,E} dV.$ (Equation 4)

The transverse shear strain energy is negligible in comparison with flexural strain energy.

$\sigma = \frac{M\,y}{I}$ for a constant cross-section, where I = the moment of inertia. Equation 4 becomes

$$U = \frac{1}{2\,E}\int_V \left[\frac{M\,y}{I}\right]^2 dV; \quad dV = dA\,dX, \text{ and}$$

$$U = \frac{1}{2\,E}\int_0^{l}\left[\frac{M^2}{I^2}\int_A y^2\,dA\right] dX = \frac{1}{2\,E}\int_0^{l}\frac{M^2}{I}\,dX. \text{ For curved lines}$$

$$U = \frac{1}{2\,E}\int_0^{S}\frac{M_\theta^2}{I}\,dS. \quad \text{(Equation 5)}$$

$S = R\,\theta$ or $dS = R\,d\theta$, and Equation 1 becomes

$$0 = \frac{\partial}{\partial M}\int_0^{\theta}\frac{M_\theta^2\,R}{2EI}\,d\theta$$ when substituting for U and dS in Equation 5.

According to Leibnitz's rule (24) differentiation and integration can be interchanged in order of operation.

$$0 = \frac{\partial}{\partial M}\int_0^{\theta}\frac{M_\theta\,M_\theta\,R}{2\,E\,I}\,d\theta = \frac{1}{2EI}\int_0^{\pi}\frac{M_\theta\,\partial M_\theta\,R}{\partial M}\,d\theta. \quad \text{(Equation 6)}$$

The bending moment at any section is expressed as follows from the free-body diagram of Figure 27c:

$$M_\theta = M + \frac{F_z R}{2}(1 - \cos\theta) - \left(\frac{F_x}{2} + \frac{M_y}{L}\right) R \sin\theta;$$ θ is defined positive clockwise in Figure 27c.

$\frac{\partial M_\theta}{\partial M} = 1$, and Equation 6 reduces to

$$0 = \frac{R}{2EI}\int_0^\pi M_\theta(1)\, d\theta\ ,$$

$$0 = \int_0^\pi \left[M - \left(\frac{F_x}{2} + \frac{M_y}{L}\right) R \sin\theta + \frac{F_z R}{2}(1 - \cos\theta)\right] d\theta,$$

$$0 = M\theta + \left(\frac{F_x}{2} + \frac{M_y}{L}\right) R \cos\theta + \frac{F_z R\theta}{2} - \frac{F_z R}{2}\sin\theta \Bigg|_0^\pi, \text{ and}$$

$$M = \frac{2R}{\pi}\left(\frac{F_x}{2} + \frac{M_y}{L}\right) - \frac{F_z R}{2}\ .$$

The bending moment at any section can now be expressed as

$$M_\theta = \frac{2R}{\pi}\left(\frac{F_x}{2} + \frac{M_y}{L}\right) - \frac{F_z R}{2} + \frac{F_z R}{2}(1 - \cos\theta) - \left(\frac{F_x}{2} + \frac{M_y}{L}\right) R \sin\theta$$

or $$M_\theta = R\left(\frac{F_x}{2} + \frac{M_y}{L}\right)\left(\frac{2}{\pi} - \sin\theta\right) - \frac{F_z R}{2}\cos\theta. \qquad \text{(Equation 7)}$$

The moment from F_x and M_y is zero when $\sin\theta = \frac{2}{\pi}$, or $\theta = 39.6^\circ$ and 140.4°, the moment from F_z is zero when $\cos\theta = 0$, or $\theta = 90^\circ$. Thus, strain nodes occur at $\theta = 39.6^\circ$ and 140.4° where only F_z can be sensed by strain gages. Similarly, M_y and F_x can be sensed at $\theta = 90^\circ$ with no effect from F_z.

This elasticity solution is not valid for node angles on the extended octagonal ring transducer. Cook and Rabinowicz (6) determined by empirical photoelastic methods that the strain nodes occur at about $\theta = 50^\circ$ and 130° for F_z and $\theta = 90^\circ$ for F_x and M_y.

Nevertheless, the analysis is useful for an approximate strength design for the extended octagonal ring transducer.

The design loads are listed as follows:

$F_x = 1000$ lb,

$F_z = 750$ lb, and

$M_y = 35{,}750$ in.-lb, predicted from the knife geometry at the time that the transducer was designed.

The bending moments at the strain nodes are calculated from Equation 7.

$$M_{50^\circ} = R\left(\frac{1000}{2} + \frac{35{,}750}{L}\right)(0.6366 - 0.7660) - \frac{750\ R}{2}(0.6428)$$

$$= -306\ R - \frac{4626\ R}{L}$$

$$M_{130^\circ} = R\left(\frac{1000}{2} + \frac{35{,}750}{L}\right)(0.6366 - 0.7660) - \frac{750\ R}{2}(-0.6428)$$

$$= 176\ R - \frac{4626\ R}{L}$$

$$M_{90^\circ} = R\left(\frac{1000}{2} + \frac{35{,}750}{L}\right)(0.6366 - 1.0000) - \frac{750\ R\ (0)}{2}$$

$$= -182\ R - \frac{12{,}992\ R}{L}$$

For typical R and L values $|M_{90^\circ}| \geq |M_{50^\circ}| \geq |M_{130^\circ}|$. Flexural stress is predominate in this situation; thus, axial and transverse shear stresses were neglected.

Stress $= \dfrac{M\ c}{I}$ and $I = \dfrac{b\ \bar{t}^3}{12}$. See Figure 27b.

Stress $= \dfrac{6\ M}{bt^2}$; Assuming a maximum allowable stress of 20,000 psi,

$\dfrac{M}{bt^2} = 3333$; for M_{90°, $\dfrac{182\ R + 12{,}992\ R/L}{b\ t^2} = 3333.$

Let $R = r + \frac{t}{2} = 1 \text{ in.} + \frac{t}{2}$,

$L = 6$ in., and

$b = 1.5$ in.

$$t^2 - 0.2348\,t - 0.4694 = 0$$

$t = 0.81$ in.

The designed extended octagonal ring is shown in Figure 28.

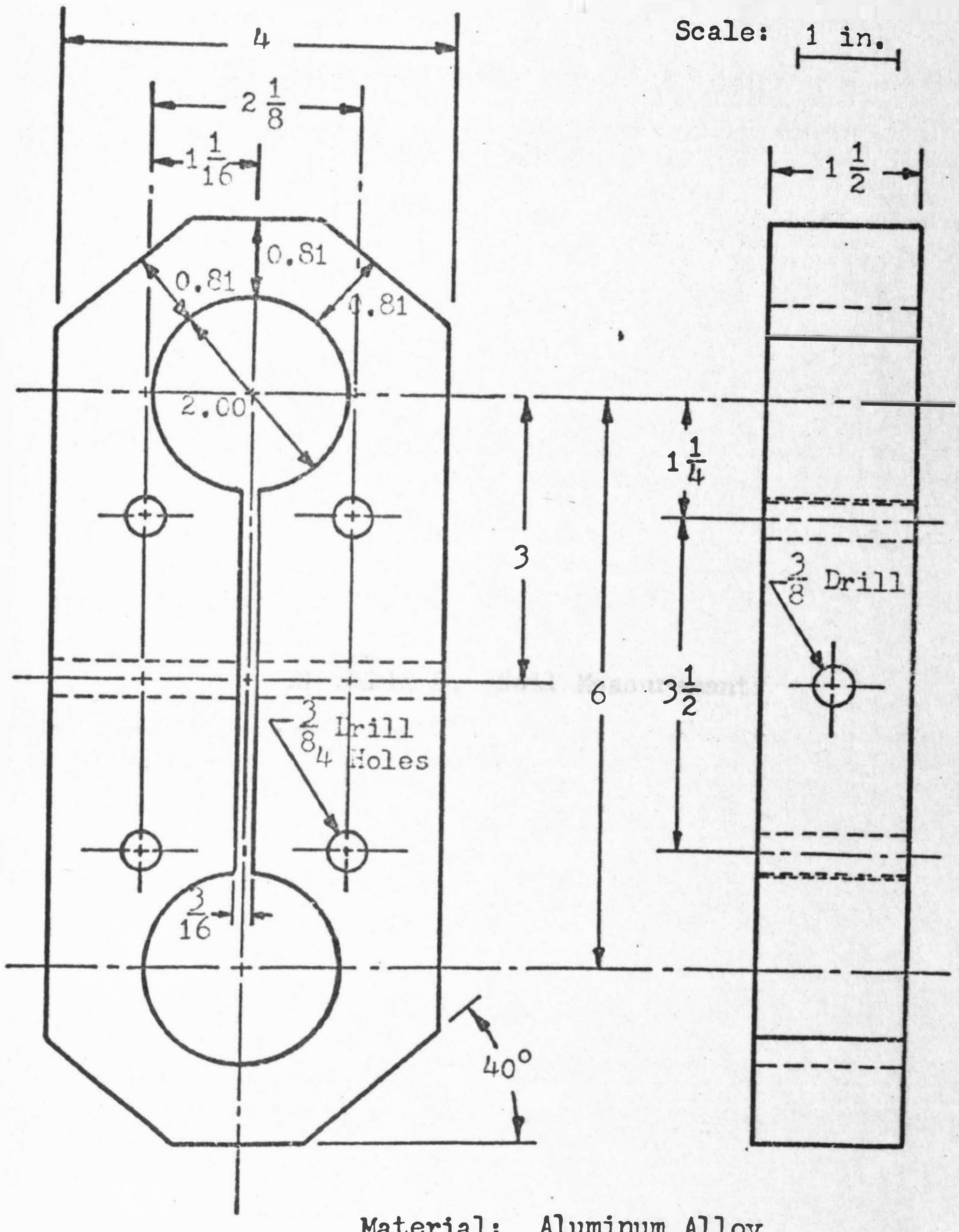

Figure 28. Extended Octagonal Ring Used for Force Transducer

APPENDIX B. Soil Measurements

Table 17. Soil Moisture Data

Moisture Condition and Date	Block	Plot	Soil Moisture (Percent Dry Basis) Surface to 3 in. Depth	3 to 6 in. Depth
High	1	5	25.9	15.7
	1	15	28.8	21.6
June 2, 1971	1	25	28.3	21.3
	2	5	29.2	19.2
	2	15	28.5	19.6
	2	25	28.4	19.0
	3	5	26.9	18.3
	3	15	31.3	20.1
	3	25	31.0	26.5
	Mean		28.7	20.1
Medium	1	5	17.0	13.4
	1	15	20.5	17.2
August 23, 1971	1	25	17.7	17.9
	2	5	18.8	14.7
	2	15	20.8	17.2
	2	25	17.9	13.5
	3	5	18.3	15.1
	3	15	21.1	16.7
	3	25	21.2	17.7
	Mean		19.2	15.9
Low	1	5	8.5	11.0
	1	15	8.1	9.6
August 3, 1971	1	25	8.0	10.7
	2	5	9.9	10.8
	2	15	8.6	11.6
	2	25	8.2	11.6
	3	5	8.4	11.0
	3	15	8.0	11.0
	3	25	8.6	11.7
	Mean		8.5	11.0

Table 18. Soil Shear and Soil-to-Metal Adhesion and Friction Coulomb Equations

Block	Plot	Test	Upper Limit From P = 0 to 5 psi	Upper Limit From P = 5 to 18 psi	Lower Limit From P = 0 to 5 psi	Lower Limit From P = 5 to 18 psi
High Moisture, June 2, 1971						
1	5	S-M*	$S = 0.5 + P \tan 35^{\circ}$	$S = 1.8 + P \tan 24^{\circ}$	$S = P \tan 31^{\circ}$	$S = 1.3 + P \tan 19^{\circ}$
1	25	S-M	$= 2.0 + P \tan 28^{\circ}$	$= 3.1 + P \tan 18^{\circ}$	$= P \tan 31^{\circ}$	$= 1.6 + P \tan 16^{\circ}$
2	15	S-M	$= 1.5 + P \tan 35^{\circ}$	$= 2.8 + P \tan 24^{\circ}$	$= P \tan 25^{\circ}$	$= P \tan 25^{\circ}$
3	5	S-M	$= 2.0 + P \tan 33^{\circ}$	$= 4.1 + P \tan 14^{\circ}$	$= P \tan 31^{\circ}$	$= 1.3 + P \tan 19^{\circ}$
3	25	S-M	$= 1.5 + P \tan 31^{\circ}$	$= 2.5 + P \tan 22^{\circ}$	$= P \tan 33^{\circ}$	$= 1.4 + P \tan 21^{\circ}$
Mean		S-M	$= 1.5 + P \tan 32^{\circ}$	$= 2.9 + P \tan 20^{\circ}$	$= P \tan 30^{\circ}$	$= 1.1 + P \tan 20^{\circ}$
1	5	S S*	$S = 1.5 + P \tan 48^{\circ}$	$S = 4.1 + P \tan 30^{\circ}$	$S = P \tan 35^{\circ}$	$S = P \tan 35^{\circ}$
1	25	S S	$= 2.0 + P \tan 40^{\circ}$	$= 2.0 + P \tan 40^{\circ}$	$= P \tan 40^{\circ}$	$= P \tan 40^{\circ}$
2	15	S S	$= 0.5 + P \tan 47^{\circ}$	$= 2.2 + P \tan 37^{\circ}$	$= P \tan 35^{\circ}$	$= P \tan 35^{\circ}$
3	5	S S	$= 1.0 + P \tan 49^{\circ}$	$= 2.3 + P \tan 42^{\circ}$	$= P \tan 40^{\circ}$	$= P \tan 40^{\circ}$
3	25	S S	$= 0.5 + P \tan 39^{\circ}$	$= 2.6 + P \tan 34^{\circ}$	$= P \tan 39^{\circ}$	$= 1.2 + P \tan 30^{\circ}$
Mean		S S	$= 1.1 + P \tan 45^{\circ}$	$= 2.6 + P \tan 37^{\circ}$	$= P \tan 38^{\circ}$	$= 0.2 + P \tan 36^{\circ}$
Medium Moisture, August 23, 1971						
1	5	S-M	$S = P \tan 22^{\circ}$		$S = P \tan 15^{\circ}$	
1	25	S-M	$= P \tan 21^{\circ}$		$= P \tan 14^{\circ}$	
2	15	S-M	$= P \tan 27^{\circ}$		$= P \tan 15^{\circ}$	
3	5	S-M	$= P \tan 21^{\circ}$		$= P \tan 13^{\circ}$	
3	25	S-M	$= P \tan 27^{\circ}$		$= P \tan 15^{\circ}$	
Mean		S-M	$= P \tan 24^{\circ}$		$= P \tan 14^{\circ}$	

*S-M refers to soil-to-metal; S S refers to soil shear.

Table 18 (Continued). Soil Shear and Soil-to-Metal Adhesion and Friction Coulomb Equations

Block	Plot	Test	Upper Limit From P = 0 to 18 psi	Lower Limit From P = 0 to 18 psi
Medium Moisture, August 23, 1971				
1	5	S S	$S = P \tan 43^{\circ}$	$S = P \tan 32^{\circ}$
1	25	S S	$= P \tan 45^{\circ}$	$= P \tan 33^{\circ}$
2	15	S S	$= P \tan 45^{\circ}$	$= P \tan 35^{\circ}$
3	5	S S	$= P \tan 45^{\circ}$	$= P \tan 35^{\circ}$
3	25	S S	$= P \tan 42^{\circ}$	$= P \tan 30^{\circ}$
Mean		S S	$= P \tan 44^{\circ}$	$= P \tan 33^{\circ}$
Low Moisture, August 3, 1971**				
1	5	S-M	$S = P \tan 27^{\circ}$	$S = P \tan 16^{\circ}$
1	25	S-M	$= P \tan 27^{\circ}$	$= P \tan 12^{\circ}$
2	15	S-M	$= P \tan 27^{\circ}$	$= P \tan 17^{\circ}$
3	5	S-M	$= P \tan 20^{\circ}$	$= P \tan 14^{\circ}$
3	25	S-M	$= P \tan 23^{\circ}$	$= P \tan 12^{\circ}$
Mean		S-M	$= P \tan 25^{\circ}$	$= P \tan 14^{\circ}$

**No soil shear readings were taken of the driest condition. It was not possible to force the shear head into the dry, hardened soil without fracturing the sample.

Table 19. Penetrometer Cone Index Readings

Moisture Condition and Date	Block	Plot	Surface	2 in.	4 in.	6 in.
			Cone Index at Depth of Cone Base			
High	1	5	50	75	110	130
	1	10	45	85	120	125
June 2, 1971	1	15	50	70	100	105
	1	20	45	80	95	105
	1	25	55	90	85	120
	2	5	60	80	85	115
	2	10	55	75	100	135
	2	15	55	75	95	130
	2	20	45	80	85	105
	2	25	55	70	75	110
	3	5	50	80	95	165
	3	10	40	65	80	105
	3	15	55	80	100	115
	3	20	55	75	80	115
	3	25	50	75	110	130
	Mean		51	77	94	121
Medium	1	5	45	140	190	220
	1	10	40	75	70	90
August 23, 1971	1	15	50	90	160	210
	1	20	60	105	170	220
	1	25	40	120	150	180
	2	5	70	120	95	140
	2	10	60	100	95	105
	2	15	45	75	100	155
	2	20	40	105	190	210
	2	25	40	85	90	120
	3	5	70	130	130	180
	3	10	40	95	115	130
	3	15	40	100	120	190
	3	20	40	75	80	135
	3	25	65	100	90	160
	Mean		50	101	123	163

Table 19 (Continued). Penetrometer Cone Index Readings

Moisture Condition and Date	Block	Plot	Surface	2 in.	4 in.	6 in.
Low*	1	5	55	170	180	210
	1	10	80	160	175	210
August 3, 1971	1	15	70	180	170	180
	1	20	120	180	180	210
	1	25	60	140	150	190
	2	5	120	180	215	230
	2	10	110	190	205	215
	2	15	60	170	180	200
	2	20	110	180	170	205
	2	25	70	130	140	140
	3	5	80	185	205	210
	3	10	90	120	180	210
	3	15	90	160	170	205
	3	20	50	140	170	195
	3	25	70	190	200	205
	Mean		82	165	179	201

*Some locations were selective because the ground was too hard to penetrate to the 6-in. depth by the weight of the operator.

APPENDIX C. Analysis of Variance

Table 20. Draft Analysis of Variance of Five Knives

Factor	Factor Symbol	Factor Level
Sample	O	2
Replication	R	3
Time	T	3
Depth	D	2
Speed	S	3
Knife	K	5

Replications are random; all other factors are fixed.

Overall Draft Mean = 495.78 lb

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
O	2491.85	1	2491.85	1.47
R	22267.77	2	11133.88	
OR	3400.37	2	1700.19	
T	4310038.00	2	2155019.00	187.63**
OT	6262.59	2	3131.29	1.58
RT	45941.11	4	11485.27	
ORT	7935.18	4	1983.79	
D	6208163.00	1	6208163.00	13677.68**
OD	166.67	1	166.67	< 1
RD	907.78	2	453.89	
ORD	407.78	2	203.89	
TD	90581.06	2	45290.53	4.37
OTD	2023.33	2	1011.67	< 1
RTD	41461.07	4	10365.27	
ORTD	10638.88	4	2659.72	
S	41167.77	2	20583.88	7.18*
OS	2284.81	2	1142.41	< 1
RS	11461.11	4	2865.28	
ORS	5626.29	4	1406.57	
TS	5761.11	4	1440.28	< 1
OTS	13317.40	4	3329.35	2.12
RTS	19403.30	8	2425.41	
ORTS	12591.43	8	1573.93	
DS	194.44	2	97.22	< 1
ODS	2434.44	2	1217.22	< 1
RDS	8854.44	4	2213.61	
ORDS	6354.44	4	1588.61	
TDS	15421.11	4	3855.28	1.51
OTDS	5885.55	4	1471.39	1.80
RTDS	20383.26	8	2547.91	
ORTDS	6538.81	8	817.35	

Table 20 (Continued). Draft Analysis of Variance of Five Knives

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
K	110732.50	4	27683.12	9.12**
OK	18600.73	4	4650.18	2.88
RK	24345.18	8	3034.15	
ORK	12923.70	8	1615.46	
TK	1367920.00	8	170990.00	36.56**
OTK	6355.92	8	794.49	< 1
RTK	74823.50	16	4676.47	
ORTK	18629.51	16	1164.34	
DK	990121.50	4	247530.38	90.75**
ODK	2114.81	4	528.70	< 1
RDK	21819.97	8	2727.50	
ORDK	13994.02	8	1749.25	
TDK	309985.25	8	38748.16	16.25**
OTDK	11584.04	8	1448.00	1.65
RTDK	38155.42	16	2384.71	
ORTDK	14036.91	16	877.31	
SK	86206.19	8	10775.77	3.48*
OSK	8811.48	8	1101.43	< 1
RSK	51042.46	16	3190.15	
ORSK	26877.29	16	1679.83	
TSK	94775.75	16	5923.48	2.62**
OTSK	21508.41	16	1344.28	1.31
RTSK	72430.75	32	2263.46	
ORTSK	32832.36	32	1026.01	
DSK	54949.94	8	6868.74	3.11*
ODSK	7772.96	8	971.62	< 1
RDSK	35367.64	16	2210.48	
ORDSK	23637.97	16	1477.37	
TDSK	45078.77	16	2817.42	1.35
OTDSK	11451.32	16	715.71	< 1
RTDSK	66898.25	32	2090.57	
ORTDSK	54805.29	32	1712.67	
Total	14660927.00	539		

**Significant at the 1 percent level.

*Significant at the 5 percent level.

Table 21. Vertical Force Analysis of Variance of Five Knives

Factor	Factor Symbol	Factor Level
Sample	O	2
Replication	R	3
Time	T	3
Depth	D	2
Speed	S	3
Knife	K	5

Replications are random; all other factors are fixed.

Overall Vertical Force Mean = 152.54 lb

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
O	342.41	1	342.41	< 1
R	3895.93	2	1947.96	
OR	898.15	2	449.07	
T	180.37	2	90.19	< 1
OT	493.70	2	246.85	1.22
RT	2516.30	4	629.07	
ORT	807.41	4	201.85	
D	83875.69	1	83875.69	45.61*
OD	81.67	1	81.67	< 1
RD	3678.15	2	1839.07	
ORD	750.00	2	375.00	
TD	43411.47	2	21705.73	14.18*
OTD	407.78	2	203.89	1.49
RTD	6122.96	4	1530.74	
ORTD	548.89	4	137.22	
S	1398.15	2	699.07	1.07
OS	127.04	2	63.52	< 1
RS	2605.19	4	651.30	
ORS	847.41	4	211.85	
TS	1434.07	4	358.52	< 1
OTS	518.52	4	129.63	< 1
RTS	8089.25	8	1011.16	
ORTS	1960.37	8	245.05	
DS	2235.93	2	1117.96	< 1
ODS	70.00	2	35.00	< 1
RDS	4778.52	4	1194.63	
ORDS	613.33	4	153.33	
TDS	2498.52	4	624.63	< 1
OTDS	575.56	4	143.89	< 1
RTDS	6113.70	8	764.21	
ORTDS	1987.77	8	248.47	

Table 22. Draft Analysis of Variance of Four Knives

Factor	Factor Symbol	Factor Level
Sample	O	2
Replication	R	3
Time	T	3
Depth	D	2
Speed	S	3
Knife	K	4

Replications are random; all other factors are fixed.

Overall Draft Mean = 500.30 lb

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
O	10305.79	1	10305.79	3.82
R	23764.34	2	11882.17	
OR	5389.35	2	2694.68	
T	5436880.00	2	2718440.00	212.59**
OT	4378.24	2	2189.12	< 1
RT	51148.14	4	12787.04	
ORT	10478.70	4	2619.67	
D	7132776.00	1	7132776.00	4605.23**
OD	316.90	1	316.90	< 1
RD	3097.69	2	1548.84	
ORD	1083.80	2	541.90	
TD	208444.69	2	104222.31	10.37*
OTD	528.24	2	264.12	< 1
RTD	40214.78	4	10053.70	
ORTD	7439.81	4	1859.95	
S	5124.07	2	2562.04	< 1
OS	301.85	2	150.93	< 1
RS	15907.86	4	3976.97	
ORS	8863.42	4	2215.85	
TS	17171.75	4	4292.94	1.91
OTS	14299.53	4	3574.88	2.19
RTS	18004.62	8	2250.58	
ORTS	13076.80	8	1634.60	
DS	4290.74	2	2145.37	2.01
ODS	2696.30	2	1348.15	1.24
RDS	4268.98	4	1067.24	
ORDS	4346.75	4	1086.69	
TDS	14655.09	4	3663.77	1.21
OTDS	4993.97	4	1248.49	1.03
RTDS	24293.42	8	3036.68	
ORTDS	9687.88	8	1210.98	

Table 22 (Continued). Draft Analysis of Variance of Four Knives

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
K	66541.38	3	22180.46	6.03*
OK	2430.32	3	810.11	< 1
RK	22057.86	6	3676.31	
ORK	10621.75	6	1770.29	
TK	102066.06	6	17011.01	3.89*
OTK	6160.64	6	1026.77	1.03
RTK	52523.90	12	4376.99	
ORTK	11926.80	12	993.90	
DK	12621.05	3	4207.02	1.71
ODK	1919.21	3	639.74	< 1
RDK	14739.34	6	2456.56	
ORDK	7371.75	6	1228.62	
TDK	82375.19	6	13729.20	4.94**
OTDK	9243.98	6	1540.66	1.42
RTDK	33353.53	12	2779.46	
ORTDK	12987.86	12	1082.32	
SK	25737.04	6	4289.50	1.79
OSK	5381.48	6	896.91	1.37
RSK	28836.46	12	2403.04	
ORSK	7881.01	12	656.75	
TSK	35311.50	12	2942.63	1.14
OTSK	14917.07	12	1243.09	1.61
RTSK	62056.32	24	2585.68	
ORTSK	18561.90	24	773.41	
DSK	24551.85	6	4091.98	1.93
ODSK	7264.81	6	1210.80	< 1
RDSK	25460.52	12	2121.71	
ORDSK	15041.95	12	1253.50	
TDSK	34624.38	12	2885.36	1.52
OTDSK	10144.78	12	845.40	< 1
RTDSK	45504.46	24	1896.02	
ORTDSK	34205.56	24	1425.23	
Total	13942618.00	431		

**Significant at the 1 percent level.

*Significant at the 5 percent level.

Table 23. Vertical Force Analysis of Variance of Four Knives

Factor	Factor Symbol	Factor Level
Sample	O	2
Replication	R	3
Time	T	3
Depth	D	2
Speed	S	3
Knife	K	4

Replications are random; all other factors are fixed.

Overall Vertical Force Mean = 176.20 lb

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
O	59.26	1	59.26	< 1
R	2647.69	2	1323.84	
OR	1564.35	2	782.18	
T	6542.13	2	3271.06	4.44
OT	2083.80	2	1041.90	4.48
RT	2946.76	4	736.69	
ORT	930.09	4	232.52	
D	100223.12	1	100223.12	48.49*
OD	156.48	1	156.48	< 1
RD	4133.79	2	2066.90	
ORD	578.24	2	289.12	
TD	37986.57	2	18993.28	14.06*
OTD	161.57	2	80.79	< 1
RTD	5402.31	4	1350.58	
ORTD	1241.20	4	310.30	
S	3344.91	2	1672.45	2.94
OS	139.35	2	69.68	< 1
RS	2273.15	4	568.29	
ORS	628.70	4	157.18	
TS	70.37	4	17.59	< 1
OTS	300.93	4	75.23	< 1
RTS	8361.57	8	1045.20	
ORTS	2331.01	8	291.38	
DS	4433.79	2	2216.90	2.68
ODS	183.80	2	91.90	1.11
RDS	3309.26	4	827.31	
ORDS	331.48	4	82.87	
TDS	6839.81	4	1709.95	2.77
OTDS	948.15	4	237.04	< 1
RTDS	4933.79	8	616.72	
ORTDS	2336.57	8	292.07	

Table 23 (Continued). Vertical Force Analysis of Variance of Four Knives

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
K	285520.25	3	95173.38	22.35**
OK	138.89	3	46.30	< 1
RK	25544.90	6	4257.48	
ORK	1531.94	6	255.32	
TK	40728.23	6	6788.04	2.51
OTK	1634.72	6	272.45	1.06
RTK	32427.19	12	2702.27	
ORTK	3073.61	12	256.13	
DK	37037.96	3	12345.98	10.47**
ODK	215.74	3	71.91	< 1
RDK	7077.31	6	1179.55	
ORDK	1588.42	6	264.74	
TDK	15746.75	6	2624.46	2.82
OTDK	916.20	6	152.70	< 1
RTDK	11175.39	12	931.28	
ORTDK	2558.79	12	213.23	
SK	12792.12	6	2132.02	5.05**
OSK	2001.39	6	333.56	< 1
RSK	5067.59	12	422.30	
ORSK	4552.77	12	379.40	
TSK	7609.25	12	634.10	< 1
OTSK	1775.00	12	147.92	< 1
RTSK	19147.56	24	797.81	
ORTSK	5504.08	24	229.34	
DSK	4821.75	6	803.62	1.60
ODSK	1127.31	6	187.89	< 1
RDSK	6012.96	12	501.08	
ORDSK	3068.52	12	255.71	
TDSK	17176.79	12	1431.40	2.95*
OTDSK	3124.07	12	260.34	< 1
RTDSK	11638.27	24	484.93	
ORTDSK	6813.28	24	283.89	
Total	786571.44	-431		

**Significant at the 1 percent level.

*Significant at the 5 percent level.

Table 24. Draft Analysis of Variance of Four Knives Including Times 1 and 2 Only

Factor	Factor Symbol	Factor Level
Sample	O	2
Replication	R	3
Time	T	2
Depth	D	2
Speed	S	3
Knife	K	4

Replications are random; all other factors are fixed.

Overall Draft Mean = 428.51 lb

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
O	3267.01	1	3267.01	< 1
R	10092.36	2	5046.18	
OR	8604.86	2	4302.43	
T	983503.06	1	983503.06	190.62**
OT	2392.01	1	2392.01	1.23
RT	10318.75	2	5159.38	
ORT	3875.69	2	1937.85	
D	3683350.00	1	3683350.00	605.86**
OD	8.68	1	8,68	< 1
RD	12159.02	2	6079.51	
ORD	1171.53	2	585.76	
TD	3403.12	1	3403.12	1.79
OTD	125.35	1	125.35	< 1
RTD	3793.75	2	1896.88	
ORTD	1200.69	2	600.35	
S	938.19	2	469.10	< 1
OS	3442.36	2	1721.18	1.22
RS	13155.55	4	3288.89	
ORS	5638.89	4	1409.72	
TS	13289.57	2	6644.79	3.00
OTS	4154.86	2	2077.43	1.65
RTS	8866.66	4	2216.67	
ORTS	5030.55	4	1257.64	
DS	63.19	2	31.60	< 1
ODS	4525.69	2	2262.85	26.07**
RDS	4580.55	4	1145.14	
ORDS	347.22	4	86.81	
TDS	3339.58	2	1669.79	< 1
OTDS	646.53	2	323.26	< 1
RTDS	11316.66	4	2829.17	
ORTDS	5130.55	4	1282.64	

Table 24 (Continued). Draft Analysis of Variance of Four Knives Including Times 1 and 2 Only

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
K	20934.36	3	6978.12	1.74
OK	1448.26	3	482.75	< 1
RK	24010.41	6	4001.73	
ORK	6759.02	6	1126.50	
TK	10051.03	3	3350.34	< 1
OTK	201.04	3	67.01	< 1
RTK	23939.57	6	3989.93	
ORTK	8010.41	6	1335.07	
DK	40176.03	3	13392.01	4.84*
ODK	3834.38	3	1278.12	2.95
RDK	16593.74	6	2765.62	
ORDK	2597.91	6	432.98	
TDK	45878.80	3	15292.93	8.65*
OTDK	6239.92	3	2079.97	3.19
RTDK	10603.46	6	1767.24	
ORTDK	3913.19	6	652.20	
SK	8422.91	6	1403.82	< 1
OSK	5929.86	6	988.31	1.24
RSK	48791.60	12	4065.97	
ORSK	9547.22	12	795.60	
TSK	2777.08	6	462.85	< 1
OTSK	6256.24	6	1042.71	1.34
RTSK	24391.54	12	2032.63	
ORTSK	9366.66	12	780.55	
DSK	24231.24	6	4038.54	1.23
ODSK	3535.41	6	589.23	1.01
RDSK	39383.25	12	3281.94	
ORDSK	6966.64	12	580.55	
TDSK	18815.96	6	3135.99	2.21
OTDSK	7275.68	6	1212.61	1.21
RTDSK	17035.98	12	1419.67	
ORTDSK	12005.40	12	1000.45	
Total	5281629.00	-287		

**Significant at the 1 percent level.

*Significant at the 5 percent level.

Table 25. Vertical Force Analysis of Variance of Four Knives Including Times 1 and 2 Only

Factor	Factor Symbol	Factor Level
Sample	O	2
Replication	R	3
Time	T	2
Depth	D	2
Speed	S	3
Knife	K	4

Replications are random; all other factors are fixed.

Overall Vertical Force Mean = 175.38 lb

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
O	425.35	1	425.35	1.56
R	1567.36	2	783.68	
OR	546.53	2	273.26	
T	5958.68	1	5958.68	4.08
OT	1467.01	1	1467.01	4.95
RT	2921.53	2	1460.76	
ORT	592.36	2	296.18	
D	130475.31	1	130475.31	530.00**
OD	217.01	1	217.01	1.35
RD	492.36	2	246.18	
ORD	321.53	2	160.76	
TD	6328.12	1	6328.12	6.24
OTD	100.35	1	100.35	< 1
RTD	2027.08	2	1013.54	
ORTD	759.03	2	379.51	
S	2671.53	2	1335.76	4.00
OS	63.19	2	31.60	< 1
RS	1334.72	4	333.68	
ORS	555.56	4	138.89	
TS	4.86	2	2.43	< 1
OTS	104.86	2	52.43	< 1
RTS	1230.56	4	307.64	
ORTS	1726.39	4	431.60	
DS	3638.19	2	1819.10	1.56
ODS	88.19	2	44.10	< 1
RDS	4672.22	4	1168.05	
ORDS	426.39	4	106.60	
TDS	4318.75	2	2159.38	4.66
OTDS	638.19	2	319.10	2.30
RTDS	1854.17	4	463.54	
ORTDS	555.56	4	138.89	

Table 25 (Continued). Vertical Force Analysis of Variance of Four Knives Including Times 1 and 2 Only

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
K	250731.50	3	83577.12	91.37**
OK	76.04	3	25.35	< 1
RK	5488.19	6	914.70	
ORK	2164.58	6	360.76	
TK	13048.25	3	4349.42	2.20
OTK	1378.82	3	459.61	3.04
RTK	11867.35	6	1977.89	
ORTK	907.64	6	151.27	
DK	16987.14	3	5662.38	31.58**
ODK	339.93	3	113.31	1.27
RDK	1074.31	6	179.05	
ORDK	534.03	6	89.00	
TDK	578.82	3	192.94	< 1
OTDK	712.15	3	237.38	1.21
RTDK	4095.13	6	682.52	
ORTDK	1174.30	6	195.72	
SK	5525.69	6	920.95	2.42
OSK	2106.25	6	351.04	1.33
RSK	4551.38	12	379.28	
ORSK	3175.00	12	264.58	
TSK	892.36	6	148.73	< 1
OTSK	553.47	6	92.25	< 1
RTSK	3888.88	12	324.07	
ORTSK	3481.94	12	290.16	
DSK	3853.47	6	642.24	1.25
ODSK	2442.36	6	407.06	2.13
RDSK	6169.44	12	514.12	
ORDSK	2293.05	12	191.09	
TDSK	12461.80	6	2076.97	17.82**
OTDSK	1236.80	6	206.13	1.31
RTDSK	1398.61	12	116.55	
ORTDSK	1886.11	12	157.18	
Total	545156.25	287		

**Significant at the 1 percent level.

*Significant at the 5 percent level.

APPENDIX D. Implement Fixed Cost and Repair and Maintenance Cost Fortran Program

```
C     IMPLEMENT FIXED COST AND REPAIR AND MAINTENANCE COST PROGRAM
C     ASSUME THAT MACHINE WAS PURCHASED FOR 0.90 OF LIST PRICE
C     N=YEARS OF OWNERSHIP TO BE 1 TO 15
C     ANNUAL USE TO BE 25 TO 500 HOURS PER YEAR IN 25 HOUR INCREMENTS
C     ANK=CONSTANT FOR REMAINING FARM VALUE
C     ACK=CORRECTION FACTOR FOR REMAINING FARM VALUE
C     RTIS=RATE OF ANNUAL CHARGE FOR TAXES, INSURANCE, AND SHELTER
C     RINT=RATE OF ANNUAL CHARGE FOR INTEREST
C     REPC1=REPAIR CONSTANT 1
C     REPC2=REPAIR CONSTANT 2
C     HRXPL=HOURS OF EXPECTED LIFE
C     ANOPH=ANNUAL OPERATING HOURS
C     COSTI=LIST PRICE
C     DEPK=DEPRECIATION CONSTANT
C     CUMOP=CUMULATIVE HOURS OF OPERATION
C     ARFVL=REMAINING FARM VALUE
C     ACDEP=ANNUAL DEPRECIATION COST
C     ACTIS=ANNUAL COST OF TAXES, INSURANCE, AND SHELTER
C     ACINT=ANNUAL COST OF INTEREST
C     ANTFC=ANNUAL TOTAL FIXED COST
C     AFCPH=ANNUAL FIXED COST PER HOUR
C     CUMRP=CUMULATIVE REPAIR AND MAINTENANCE COST
C     ANFCR=TOTAL ANNUAL FIXED AND R&M COST
C     ACPHO=ANNUAL FIXED AND R&M COST PER HOUR
C     HAVRP=ANNUAL R&M COST PER HOUR
C     AVCUR=AVERAGE CUMULATIVE R&M COST PER HOUR
C     CUMFC=CUMULATIVE FIXED COSTS
C     HATFC=AVERAGE CUMULATIVE FIXED COST PER HOUR
C     CUMTC=CUMULATIVE TOTAL COST OF FIXED AND R&M COSTS
C     HCSTA=AVERAGE CUMULATIVE FIXED AND R&M COSTS PER HOUR OF OPERATION
      DIMENSION CUMOP(15),ARFVL(15),ACDEP(15),ACTIS(15),ACINT(15),
     1ANTFC(15),AFCPH(15),K(15),CUMRP(15),ANCRP(15),ANFCR(15),
     2ACPHO(15),HAVRP(15),CUMFC(15),HATFC(15),CUMTC(15),HCSTA(15),
     3AVCUR(15),NAME(24)
```

```
800 READ (11,803) NAME
803 FORMAT (24A3)
    WRITE (12,804) NAME
804 FORMAT (1H1,40X,24A3)
    READ (11,700)ANK,ACK,RTIS,RINT,REPC1,REPC2,HRXPL
700 FORMAT (7F10.5)
    WRITE (12,801)
801 FORMAT (1H0,6X,'DEP1',13X,'DEP2',9X,'TAX INS SHELT',4X,'INTEREST R
   *ATE',6X,'REPAIR 1',9X,'REPAIR 2',9X,'LIFE HOURS')
    WRITE (12,802) ANK,ACK,RTIS,RINT,REPC1,REPC2,HRXPL
802 FORMAT (1H0,5X,F6.3,10X,F8.5,10X,F6.3,11X,F6.3,9X,F7.5,12X,F4.2,
   *14X,F8.1)
    WRITE (12,501)
501 FORMAT (1H0,6X,'CUMULATIVE AVERAGE FIXED AND R&M COSTS PER HOUR OF
   1 OPERATION IN DOLLARS PER 1000 DOLLAR LIST PRICE OF IMPLEMENT')
    WRITE (12,502)
502 FORMAT (1H0,50X,'AGE IN YEARS')
    WRITE (12,503)
503 FORMAT (1H ,1X,'HRS. PER YEAR      1       2       3       4       5
   1 6       7       8       9      10      11      12      13      14      1
   25')
201 ANOPH=25.
202 CONTINUE
203 COSTI= 1000.
212 DEPK=1.000-ANK
    SN=HRXPL/ANOPH
    NN=SN
    IF(NN-15) 300,214,214
300 N=NN&1
    GO TO 215
214 N=15
215 DO 600 J=1,N
600 K(J)=J
  8 DO 10 J=1,N
```

```
  9 B=J
 10 CUMOP(J)=ANOPH*B
 12 ARFVL(1)=0.90*COSTI
 13 ACDEP(1)=0.90*COSTI-(COSTI*AOK*ANK)
 14 DO 17 J=2,N
 15 C=J-1
 16 ARFVL(J)=AOK*(ANK**C)*COSTI
 17 ACDEP(J)=DEPK*ARFVL(J)
216 DO 218 J=1,N
 19 ACTIS(J)=RTIS*ARFVL(J)
 20 ACINT(J)=RINT*ARFVL(J)
 27 ANTFC(J)=ACDEP(J)&ACTIS(J)&ACINT(J)
218 AFCPH(J)=ANTFC(J)/ANOPH
219 DO 221 J=1,N
221 CUMRP(J)=REPC1*COSTI*(((CUMOP(J)/HRXPL)*100.)**REPC2)
224 ANCRP(1)=CUMRP(1)
226 DO 228 J=2,N
228 ANCRP(J)=CUMRP(J)-CUMRP(J-1)
230 DO 235 J=1,N
 29 ANFCR(J)=ANCRP(J)&ANTFC(J)
 32 ACPHO(J)=ANFCR(J)/ANOPH
232 HAVRP(J)=ANCRP(J)/ANOPH
235 AVCUR(J)=CUMRP(J)/CUMOP(J)
237 CUMFC(1)=ANTFC(1)
238 HATFC(1)=CUMFC(1)/ANOPH
239 DO 241 J=2,N
240 CUMFC(J)=CUMFC(J-1)&ANTFC(J)
241 HATFC(J)=CUMFC(J)/CUMOP(J)
 36 CUMTC(1)=ANFCR(1)
 38 DO 40 J=2,N
 40 CUMTC(J)=CUMTC(J-1)&ANFCR(J)
 42 DO 44 J=1,N
 44 HCSTA(J)=CUMTC(J)/CUMOP(J)
    WRITE (12,531) ANOPH,(HCSTA(J),J=1,N)
```

```
531 FORMAT (1H0,4X,F6.1,5X,15F7.2)
400 IF(ANOPH-475.) 401,401,800
401 ANOPH=ANOPH&25.
402 GO TO 202
    END
```

Table 21 (Continued). Vertical Force Analysis of Variance of Five Knives

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	Calculated F
K	1495360.00	4	373840.00	113.43**
OK	3078.89	4	769.72	2.72
RK	26365.18	8	3295.65	
ORK	2344.44	8	283.06	
TK	80158.44	8	10019.80	4.74**
OTK	4982.22	8	622.78	2.75*
RTK	33789.14	16	2111.82	
ORTK	3627.77	16	226.74	
DK	53593.69	4	13398.42	13.33**
ODK	313.70	4	78.43	< 1
RDK	8038.51	8	1004.81	
ORDK	1896.29	8	237.04	
TDK	16194.07	8	2024.26	2.66*
OTDK	1060.74	8	132.59	< 1
RTDK	12193.60	16	762.10	
ORTDK	4415.88	16	275.99	
SK	17007.40	8	2125.93	5.86**
OSK	2026.66	8	253.33	< 1
RSK	5800.36	16	362.52	
ORSK	4843.33	16	302.71	
TSK	12493.68	16	780.86	1.06
OTSK	2105.55	16	131.60	< 1
RTSK	23655.07	32	739.22	
ORTSK	9321.02	32	291.28	
DSK	8691.85	8	1086.48	1.53
ODSK	1576.29	8	197.04	< 1
RDSK	11349.17	16	709.32	
ORDSK	4607.00	16	287.94	
TDSK	24673.58	16	1542.10	3.23**
OTDSK	3922.52	16	245.16	< 1
RTDSK	15275.05	32	477.35	
ORTDSK	8797.29	32	274.92	
Total	2087407.00	-539		

**Significant at the 1 percent level.

*Significant at the 5 percent level.